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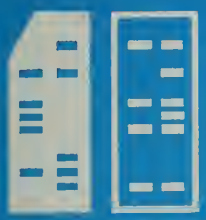
CAECOTRON:
A TUBE FOR THE BLIND

by

Bernard Ka Pang Tse

March, 1975



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A TUBE FOR THE BLIND

by

Bernard Ka Pang Tse

March, 1975

Department of Computer Science
University of Illinois
Urbana, Illinois 61801

This work was supported in part by the Regional Health Resource Center and was submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Electrical Engineering at the University of Illinois, Urbana, Illinois, March, 1975.

CAECOTRON: A TUBE FOR THE BLIND

Bernard Ka Pang Tse, Ph.D.
Department of Electrical Engineering
University of Illinois at Urbana-Champaign, 1975

ABSTRACT

Caecotron is a project in visual prostheses that derives visual information from two television cameras and outputs the information to the user, namely a visually deprived person, in the form of a modulated tone sequence. The aural picture consists of a 16 X 16 matrix mapped onto the field of the television cameras and the audio system scans across this matrix picture in a way similar to that in which a television camera scans its field. Each of the 16 lines is represented in the aural picture by a distinct frequency and each of the 16 cells of each line is displayed serially: Frequency shifts correspond to brightness variations, while an amplitude modulation of the tone corresponds to the distance of a given element.

Acknowledgements

The author is deeply grateful to Professor W. J. Poppelbaum, Director of the Information Engineering Laboratory at the University of Illinois, who suggested the thesis topic and provided invaluable support and encouragement. Beginning from that February morning in 1970 when the author went to him with his many problems, Professor Poppelbaum's generosity with his valuable time and his kind friendship have been very much appreciated.

The author also wants to thank Professor W. J. Kubitz for his valuable suggestions and frank criticisms during the implementation of Caecotron.

Messrs. Frank Serio, Bill Marlatt and Sam McDowell of the printed circuit laboratory were most helpful during the construction phase of the project. Ms Evelyn Huxhold typed portions of this thesis. The author likes to thank them for their very fine efforts.

The author also likes to express his thanks to Grace who helped to make life a lot livelier.

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1. Introduction

Caecotron -- a tube for the blind -- as proposed by Professor Poppelbaum is a project in visual prostheses that derives visual information from two television cameras and outputs this information to the user, namely a visually deprived person, in the form of a modulated tone sequence. Both brightness (black/white) and depth information are derived from the video signal of the two side-by-side television cameras and presented to the user. However, due to the limited bandwidth of the human ear as compared to that of the human eye, the amount of information that can be extracted from the video signals has to be condensed and drastically simplified.

In the actual system, the 'picture' presented to the user consists of a 16 X 16 matrix mapped onto the field seen by the television cameras. The audio system scans across this matrix picture in a way similar to that in which a television camera scans across its field (although there is no interlace.) Each of the 16 lines is represented in the aural picture by a distinct frequency and each of the 16 'cells' of a particular line is displayed serially: Frequency shifts correspond to brightness variations, while an amplitude modulation of the tone corresponds to the distance of a given element.

In order to determine depth, an electronic telemetry system using two television cameras is used. These two cameras are mounted side-by-side and are situated at about eye level. By measuring the relative 'shift' of the signal of the left-hand camera as compared to the signal of the right-hand camera, depth information can be extracted. This depth information is used to amplitude modulate the output as described in the previous paragraph. Since all of the information available from the two television cameras is not utilized in the output to the user of Caecotron, various interesting

options can be added to the basic system: Instead of operating on an entire TV frame, attention can be focused on a smaller section of the picture. Hence it is possible to achieve a close-in view of the object of interest. This idea can be further extended to simulate the effects of variable focal length lenses on the cameras by restricting the system to different-sized sections of the television picture.

Such a system has been implemented at the Information Engineering Laboratory of the University of Illinois to study the feasibility and usefulness of such a machine. This thesis represents the system design of Caecotron; and, in the pages following, the functions and design of Caecotron as well as its sub-systems are described.

2. An Overview of Caecotron

Caecotron is basically a fairly low resolution TV camera with an aural output. It has an electronic telemetry system that uses a simple algorithm to determine depth information about the objects that it is looking at. However, before going into the description of the design of the system, it is worthwhile to look, in some detail, into some of the things that Caecotron does.

To begin with, Caecotron converts a television picture into a 16 X 16 sound picture. The latter is displayed to the user as a 16-step tone sequence, beginning at the top of the picture, represented by the highest note in the sequence, and ending at the bottom of the picture, represented by the lowest note of the sequence. Each note is sub-divided into 16 time slots, with each slot representing a 'cell' of the 16-cell matrix lines. In other words, the 16-step tone sequence displays the television picture serially from the top left to the bottom right just like a TV monitor displays the video picture, but, in this case, the display is aural instead of visual.

The choice of tones in the 16 step tone sequence is important, however, since these tones should be easily recognizeable and, what is more, they should fall within a fairly narrow range of the audio spectrum so as to accommodate people with limited hearing capabilities. During the early phases of the project, experiments were done to determine the ability of the ear to distinguish tones and tone sequences. It was found that for a given percentage change in the frequency, the ear can more readily detect a change in frequency for a square wave than for a sine wave. This is not unreasonable

since a change in the repetition rate of a square wave creates a change in each of its overtones. For this reason, square wave tone sequences were chosen for the aural pictures.

An upper frequency of about 2112 Hz, a C, was chosen for the top line of the aural picture. 15 other tones, each one lower in frequency than the one preceeding and within a few percent of a corresponding note in the well-tempered scale, were chosen as the fundamental frequencies of the other 15 other aural lines. In this case, the lowest note has a frequency of 495 Hz ---------- a B. Such a tone sequence easily falls within the hearing range of most people; and if these tones are played in sequence, they can easily be recognized by non-musical operators of the system. A table of these tones and their frequencies is shown in Figure 1.

It was also mentioned in the Introduction that each of the 16 X 16 cells is presented to the user either as black or white in shade. A cell is considered to be white if the location in space corresponding to the particular cell is brighter than a pre-established average value of brightness as determined by the previous line. Otherwise the cell is considered to be black. If, for example, a black cell is located on a white line, then this balck cell is represented to the user as a slight elevation in the tone frequency in the time slot corresponding to that particular black cell. In other words, the 16 step tone sequence is <u>frequency modulated</u> to display the sensation of brightness (i.e. the blackness or whiteness of particular cells.)

It was also discovered by the early experimentation that a change of 1/64 of the fundamental frequency (less than a half tone) can be noticed without much difficulty. Consequently, when the system encounters a black cell as it scans across a matrix line, the frequency of the aural line is

Line number	Tone	Frequency
1	C"	2112
2	B'	1980
3	A'	1760
4	G'	1584
5	F'	1408
6	E'	1320
7	D'	1188
8	C'	1056
9	B	990
10	A	880
11	G	792
12	F	704
13	E	669
14	D	594
15	C	528
16	B	495

Figure 1. Caecotron Tone Frequencies

increased by 1/64 of that of its fundamental frequency. An example of a display pattern to demonstrate the scheme described above is shown in Figure 2.

The loudness with which the tone picture is displayed tells the user approximately how far the majority of the objects in the picture is away from the user. If the intensity of the aural picture is high, it means that there is the possibility of having some object very close to the user, i.e. the intensity of the aural picture alerts the user to a possible danger! On the other hand, if the aural picture is displayed with a relatively low intensity, it means that most of the objects in the field of view are probably fairly far away.

In the Caecotron system, 5 loudness levels of the tone sequence are used to display the distance information. These loudness levels correspond approximately to objects situated at infinity, 13 feet, 7 feet, 4.5 feet and for the highest intensity level, a distance of about 3.5 feet. (It will be shown in a later section how these distances are arrived at and why they are used.) It may be observed that the resolution of this system is biased in the 3 feet to 15 feet region; however, this cannot be considered to be a liability since this region is generally the area that we are most interested in, while in most circumstances, whether an object is 500 feet away from the observer or whether it is 600 feet away is of little importance.

The Caecotron system is also capable of 'magnifying' certain areas of the displayed picture so that particular arears of interest can be given a more detailed 'look'. Caecotron is able to examine a field of view corresponding to the center 1/4 and 1/16 of the standard TV format in addition to the full television field. This gives the system extra versatility when the ordinary 16 X 16 resolution of the displayed picture does not give enough

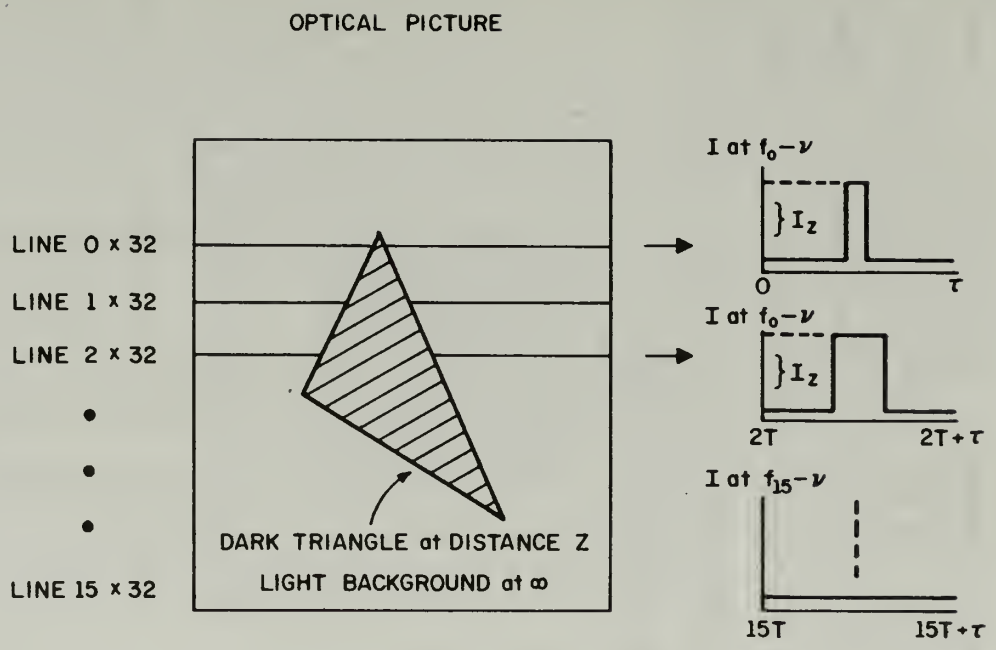


Figure 2. An Acoustical Picture

detail of specific areas to the user. A portion of the picture, namely the areas around the center of the field of view of the cameras, can be selectively magnified to extract finer details. If a still closer look of the picture is required, then the center 1/16 can be magnified for scrutiny. Figures 3, 4 and 5 show the areas of a normal TV picture that is included in the display when magnifications of X1, X2 and X3 are used. The number of vertical lines indicated in the figures corresponds to the appropriate number of vertical lines that make up an individual matrix line; and, the amount of time designated in the figures corresponds approximately to the portion of a horizontal TV line occupied by the appropriate cells.

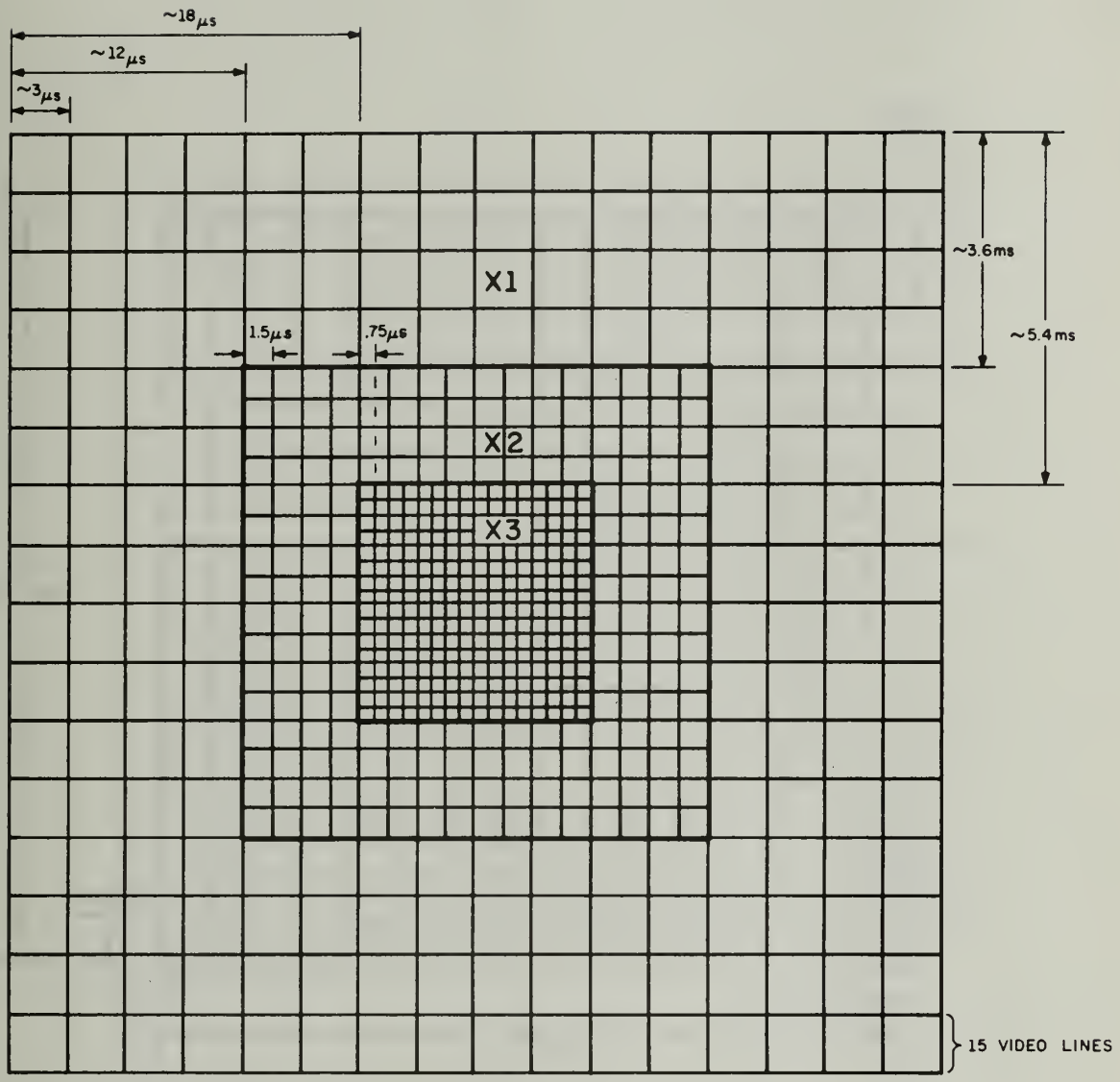


Figure 3. The Format of the Matrix Picture

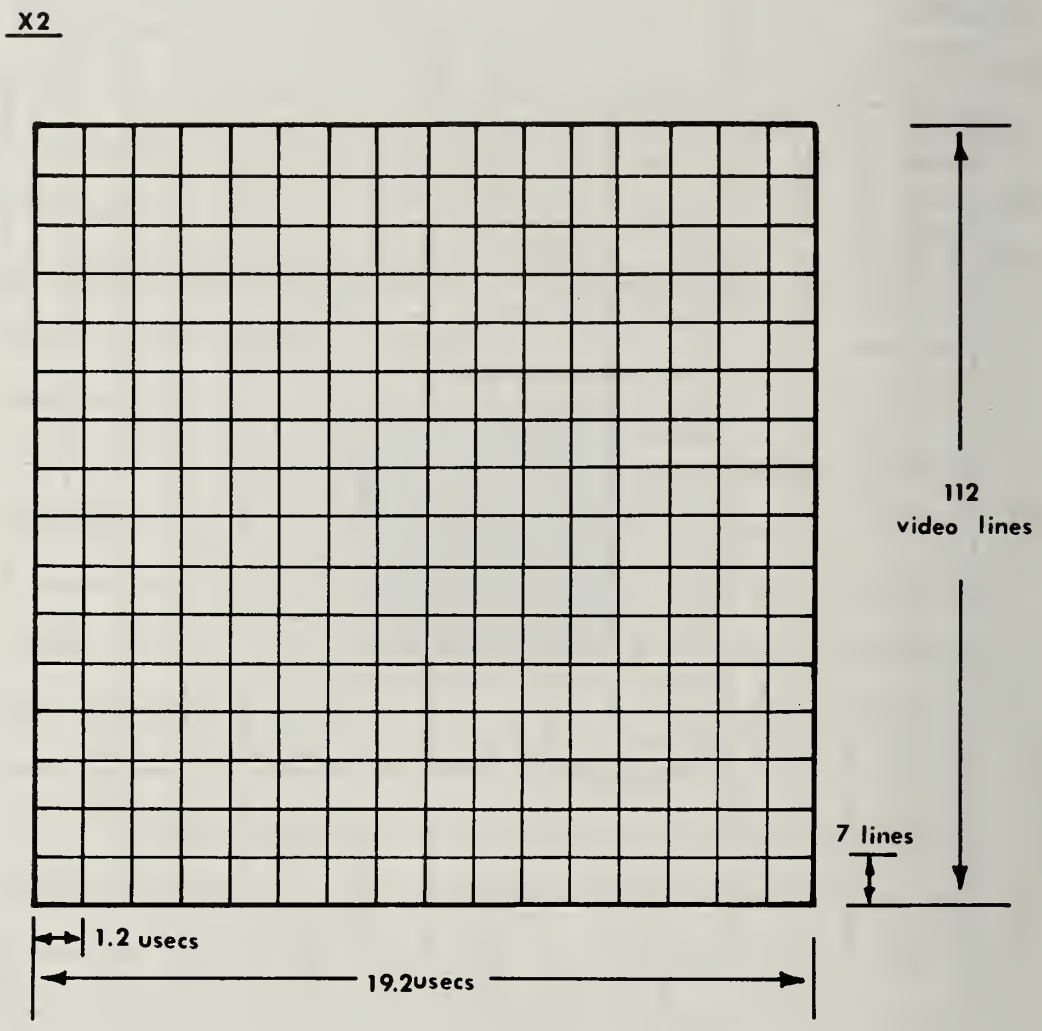


Figure 4. Picture Format for a Magnification of X2

X3

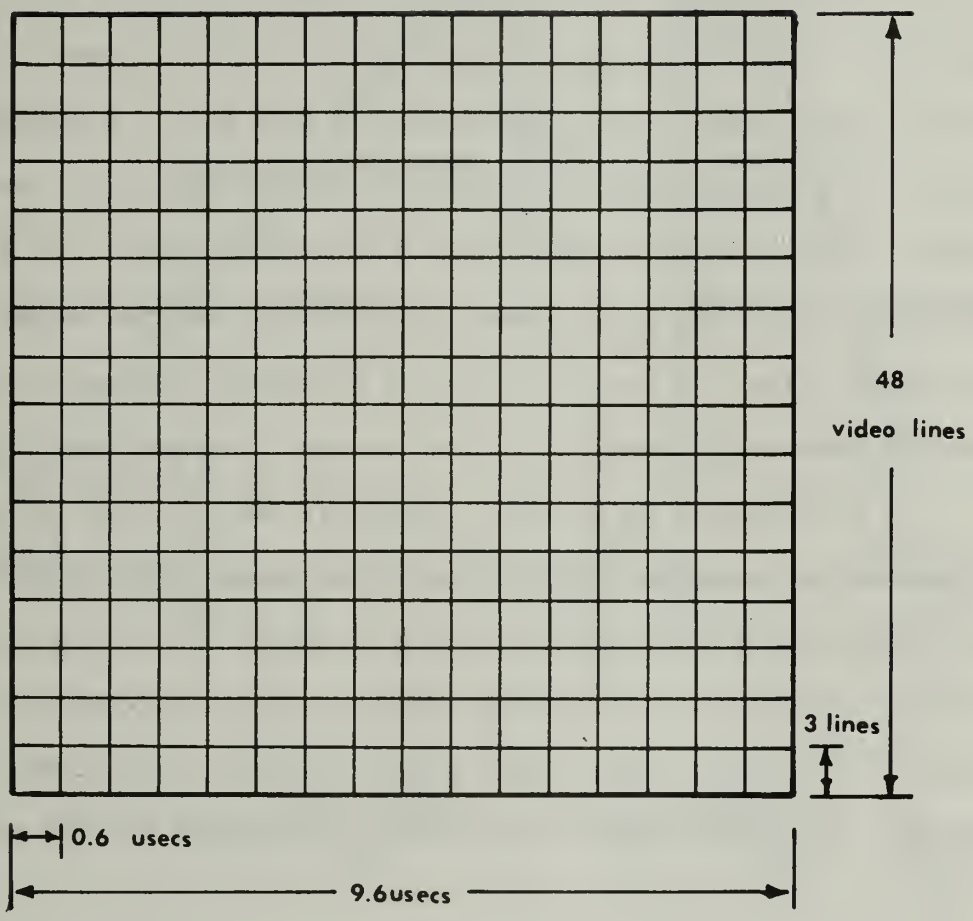


Figure 5. Picture Format for a Magnification of X3

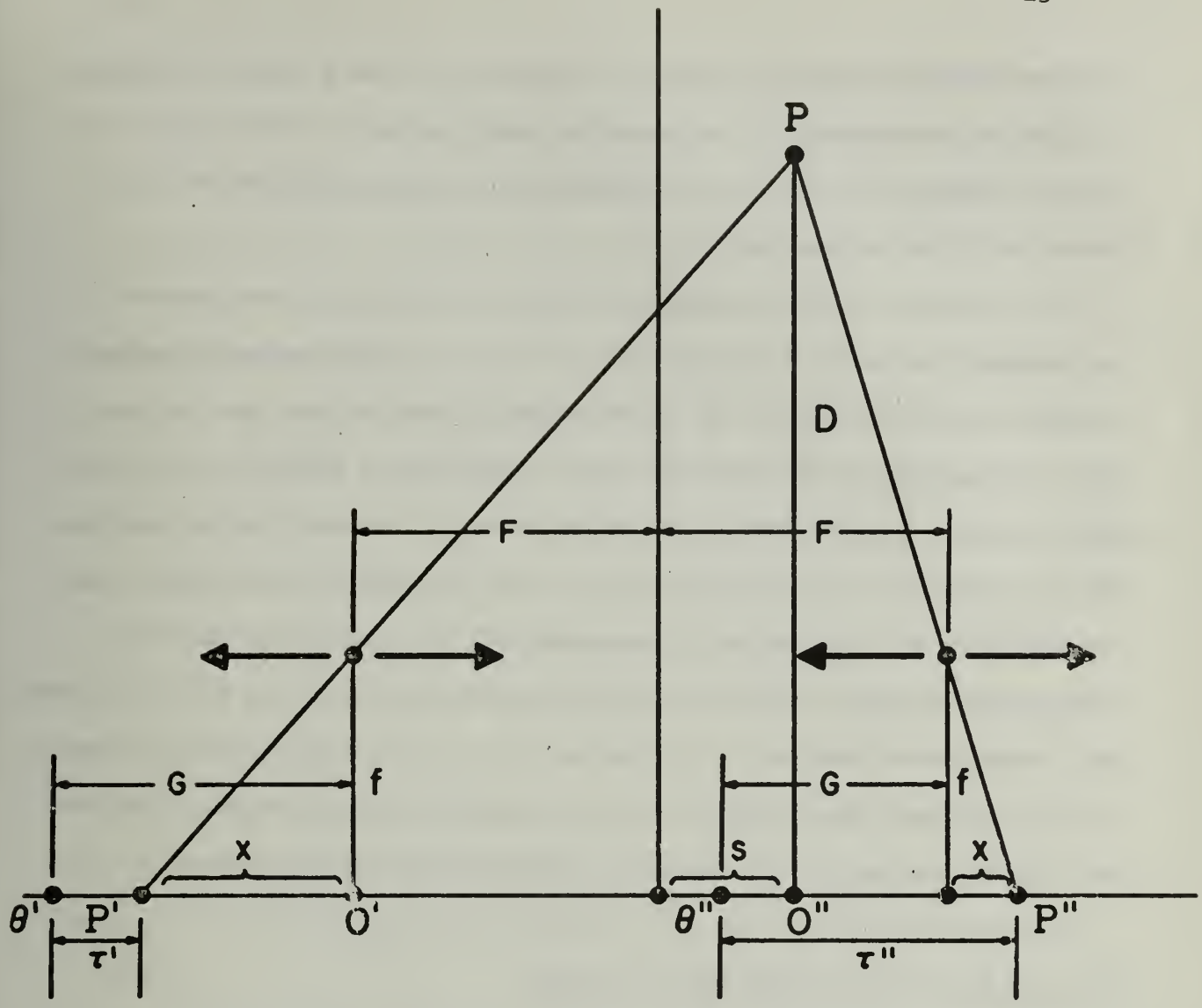
3. The Caecotron Telemetry System

3.1 Caecotron Telemetry

The telemetry of the Caecotron system involves a simple idea: The right-hand view as seen from the human eye is a shifted version of the left-hand view, and, what is more, the amount of this shift is inversely proportional to the distances that the objects in the field of view are away from the eyes. Our eyes, for example, are 3 to 4 inches apart, and the optical information (left and right views) obtained by the eyes are processed in some manner inside our brains to give us the depth information we need. The telemetry system of Caecotron utilizes exactly the same basic idea!

As mentioned in previous chapters, Caecotron has two television cameras that are mounted horizontally next to each other. The two camera lenses are mounted about 8 inches apart to obtain the left-eye view and the right-eye view for the system. The phase shift between the two camera signals (or the time delay of one signal relative to the other) gives us, as in the case of the eyes, the infromation necessary for the determination of depth.

Before continuing, it is perhaps worthwhile to dwell momentarily on the idea behind the telemetry system used in Caecotron. Figure 6 gives a graphical representation of the description of the preceeding paragraphs. The pair of points from which the two pairs of arrows originate represents the centers of two lenses of focal lengths f, separated by a distance of 2F, that are placed a focal length away from the two vidicon camera tubes. Such



$$x' \cong \frac{(F+s)f}{D} \qquad x'' \cong \frac{(F-s)f}{D} \quad (\text{if } x \times f << D)$$

$$G - \tau' \cong \frac{(F+s)f}{D} \qquad \tau'' - G \cong \frac{(F-s)f}{D}$$

$$\therefore \qquad \tau'' - \tau' \cong \frac{f}{D} \cdot 2F$$

Figure 6. Caecotron Telemetry

a system represents the two cameras of Caecotron. P is a point of distance D in front of the cameras and the straight lines joining P to the centers of the two lenses and the vidicon photosensitive surfaces represent two light paths from P to the cameras.

As shown by the derivation in Figure 6, the time delay between the signals that point P impresses on the left and right cameras is proportional to the focal lengths of the two lenses, namely f, and the distance that the two cameras are separated, 2F. What is more, this time delay is also inversely proportional to the distance tha P is away from the cameras. This proportionality is utilized in the telemetry system of Caecotron: By comparing the left-hand view of the system with the right-hand view and shifted (or delayed) versions of the right-hand view, we can find the optimal match that can be obtained by such a procedure. This optimal amount of delay of the right hand camera signal tells us approximately the distance that the majority of the objects in view are located in front of the cameras.

3.2 The Left and the Right Matrix Pictures

It was described in the two previous chapters that the aural picture is presented to the user of the system as a 16-step tone sequence with each tone representing a line of the matrix picture, and that each line is made up of 16 equally spaced cells. In order to generate this matrix picture from the standard television video signals, the latter have to be integrated over a cell period, and if the integral corresponding to a particular cell period is larger in magnitude than a certain predetermined threshold ------ in this case, the threshold is set by the integral of the previous television line ------- then the cell is considered to be white. By using this criterion on both the left and the right video signals, two matrix pictures can be

generated. Figure 7 shows the format of such a matrix pair. (It is important to note that the cell periods are identical on both matrices.)

In the telemetry procedure outlined in Section 3.1.1, each line of the left-hand view is compared with the corresponding line of the right-hand view and also delayed versions of the latter. Since the cell length is chosen to be the basic amount of each delay of the right-hand matrix picture, it explains why the left-hand matrix has to be 16 X 20 while the right-hand version is only 16 X 16! First of all, cells 1 through 16 of the left-hand matrix picture are compared with cells 1 through 16 of the right-hand version; and, such an operation represents the comparison process of the unshifted versions of the two matrices. A comparison of the left-hand matrix with a n-cell delayed version of the right-hand matrix corresponds merely to the comparison of cells 1 through 16 of the right-hand matrix with cells n+1 through n+16 of the matrix on the left! In Caecotron, since n has a maximum value of 4, the left hand matrix picture has to have a dimension of 16 X 20. This can be sumarized by the 4 step procedure shown in Figure 8.

Figure 9 shows the left and right matrix pictures that are generated by a hypothetical black rectangle situated on a white background. It shows that the rectangle as seen by the left camera is obviously shifted by a greater amount from the leading edge of the matrix when compared to the position of the black rectangle on the right matrix picture. If the telemetry procedure described above is followed, it can be fairly easily shown that the best match can be found by shifting the right-hand picture 4 cells to the right. This shows that the black rectangle is fairly close to the observer. The exact distance that the rectangle is away from the user is, of course, as shown in the beginning of the chapter, also dependent on the focal lengths

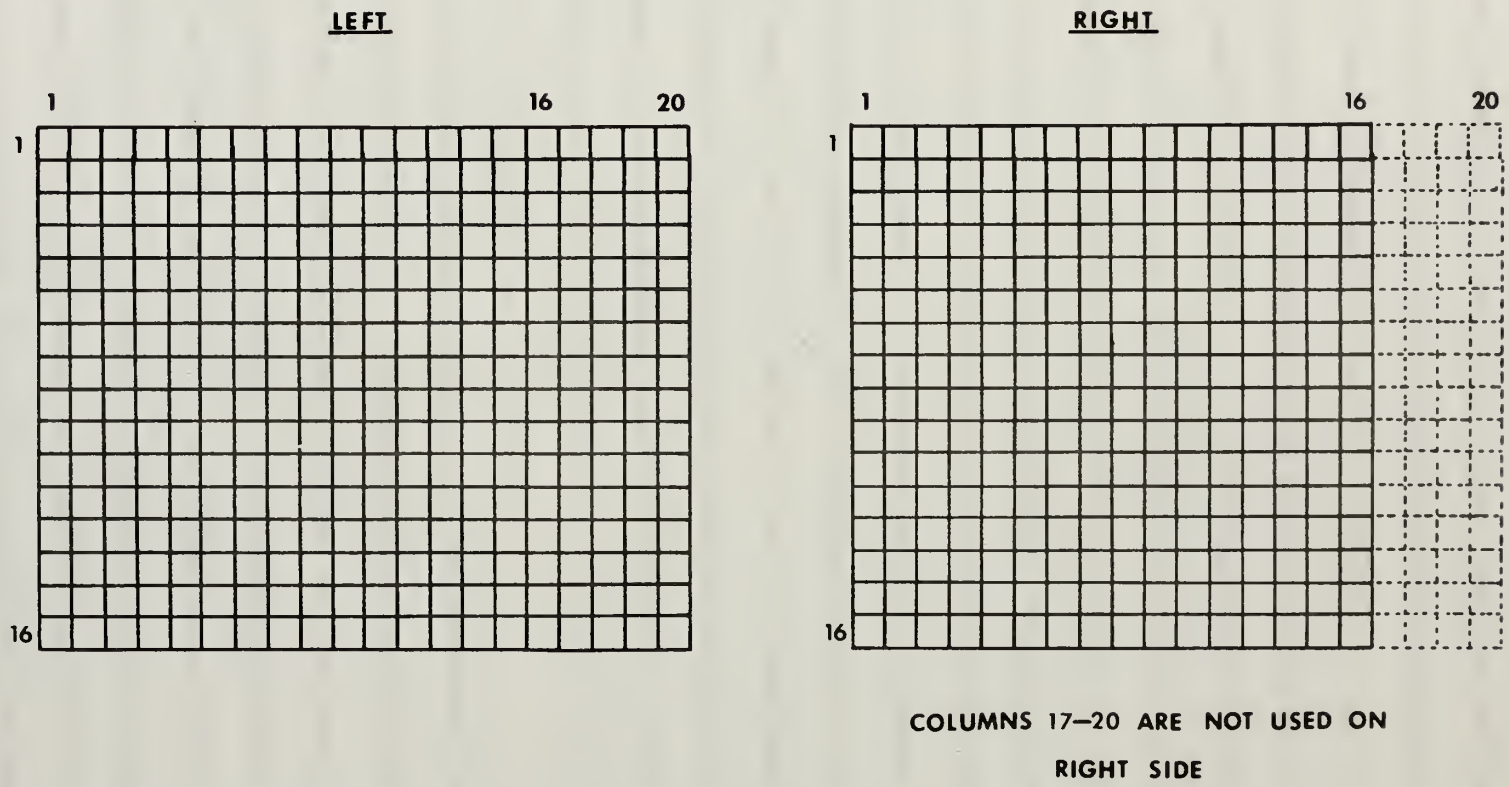
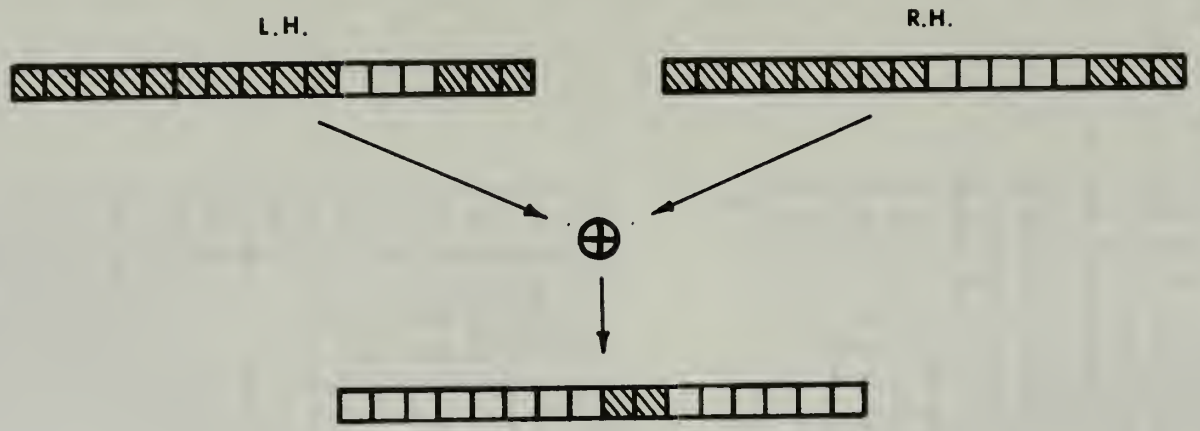


Figure 7. The Format of the Left and Right Matrix Pictures

(1)



(2) Sum up black squares

(3) Shift L.H. left by one square

(4) Repeat from (1)

Figure 8. A Sumarization of the Rangefinding Procedure

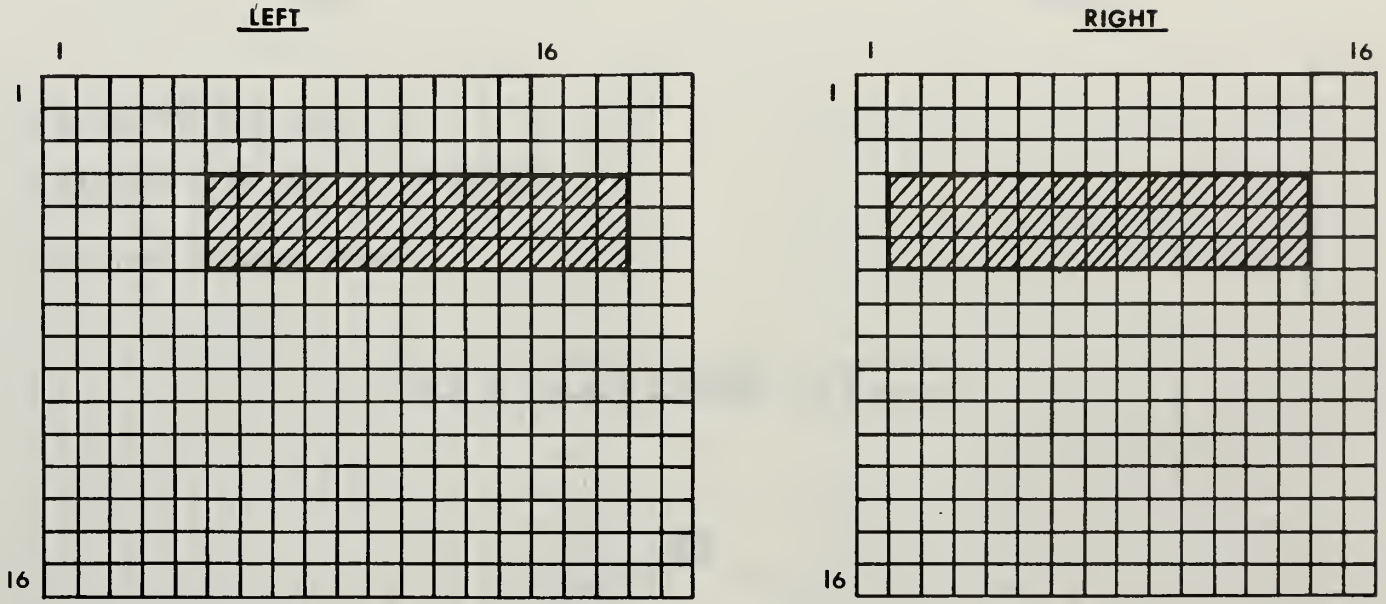


Figure 9. A Possible Left and Right Matrix Pair

of the lenses used and the distance that they are placed apart. As an example, when two 25 mm (or 1 inch) lenses are used on two 1 inch vidicon cameras that are placed 8 inches apart, a shift of 1 cell corresponds to a distance of about 13 feet. Shifts of 2 and 3 cells correspond to distances of 7 and 4.5 feet respectively, while a shift of 4 cells indicates that the object is only about 3.5 feet from the observer.

Figure 10 shows the relationship between the amounts of shift of the left picture matrix and the object distance when the above cameras are used on the Caecotron telemetry system.

Object Distance	Separation of the Two Cameras 7"	8"	9"	10"	11"	12"
Amount of Shift						
0		I N F I N I T Y				
1	12'	13'	15'	17'	18'	20'
2	6'	7'	8'	8.5'	9'	10'
3	4'	4.5'	5'	5.5'	6'	7'
4	3'	3.5'	4'	4'	4.5'	5'

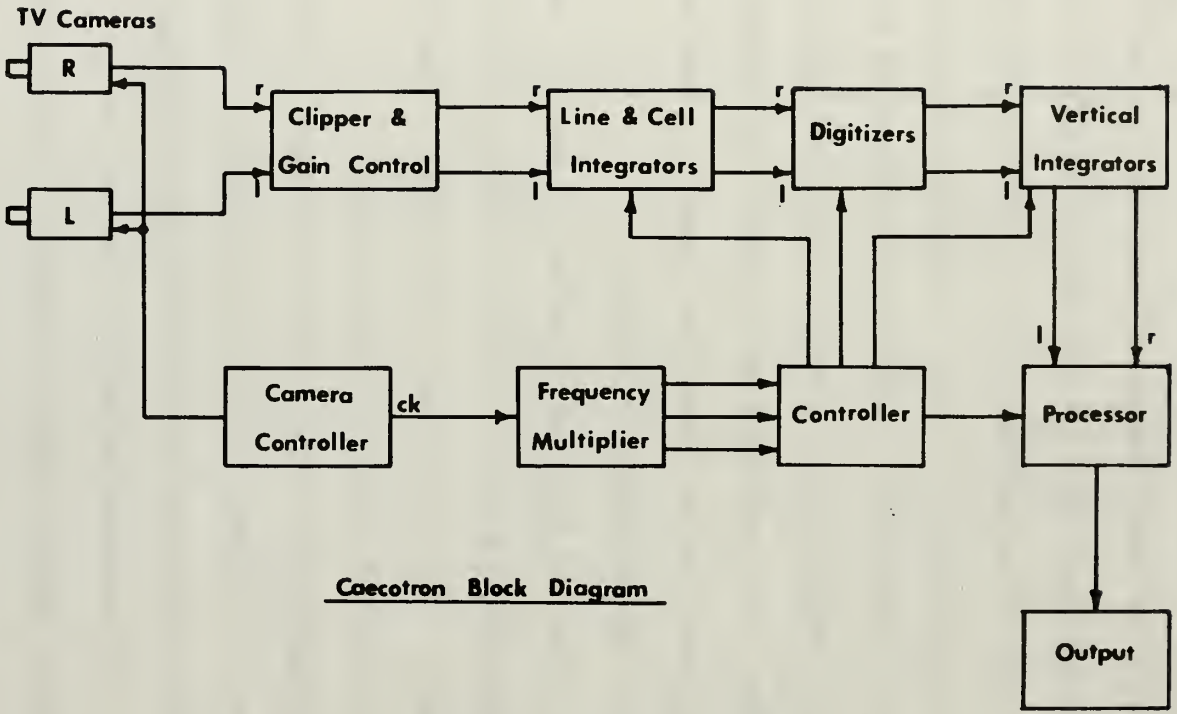
Figure 10. Object Distance as a Function of Camera Separation and Amount of Picture Shift

4. System Description of Caecotron

As described earlier, a two camera telemetry system is employed to determine the depth information. Two Cohu cameras with associated Camera Controllers are presently being used in the Caecotron system. The camera controller, as shown in the block diagram of Caecotron in Figure 11, supplies all the synchronization signals that the two cameras require, as well as the basic 31.5 kHz clock of the system. From the latter, clock signal of 13 X 31.5 kHz, 26 X 31.5 kHz and 53 X 31.5 kHz are derived using the Frequency Multiplier. These clock frequencies correspond respectively to the case when the system is in the X1 magnification state, X2 magnification state and the X3 magnification state; and, depending on the magnification state that the machine is operating under, one of these clock signals is used as the system clock that control all the functions of Caecotron.

The signals form the television cameras are amplified and conditioned by the Clipper and Gain Control which strips the standard video of all the synchronization signals, and, what is more, establishes a black level reference for the integrators inthe following section.

The Line Integrators integrate the video signal of each of the horizontal lines; and, this signal serves as the standard brightness, or pre-established average brightness level for the Cell Integrators during the following line. This standard brightness reference derived from the previous line is used in Caecotron mainly because it tends to enhance contrast and, under certain circumstances, also tends to bring out extra features which may be lost when a fixed reference is used. This is very well exemplified by the case when there is a sharp difference in brightness level between the top



Caecotron Block Diagram

Figure 11. Caecotron Block Diagram

half and the bottom half of a picture. If a fixed reference level is used in this case, the matrix picture will probably show only the sharp difference in brightness level of the two halves, while the finer details within these regions will probably be lost.

Using the average brightness level and cell integrals supplied by the line and cell integrators, the Digitizer and Vertical Cell Integrators reduce the video signals into the matrix pictures. The digitizer compares the cell integral with the reference brightness level and determines whether the particular cell is white or black. With this information, the vertical cell integrators sum up the white cells in each of the components of the 16 line matrices, and, if the number of white cells in an element exceed a certain level, then the particular element is considered to be white.

With the left and the right matrix pictures provided by the system described so far, the Processor determines how far the majority of the objects in the field of view of the cameras is away from the user. The idea behind its operation is described in Chapter 3 and essentially involves the comparison of the left matrix picture with the right pictur matrix as well as shifted versions of the latter.

All these operations are controlled by the block labelled 'Controller' which contains the majority of the circuits needed for the control of the active RC integrators and vertical integrators, as well as for the generation of the timing and control signals necessary for the rangefinding process. The Output circuits contain primarily the tone generators that produce the 16-step tone sequence for the output of the aural picture, as well as the circuits that produce the slight elevations of these 16 frequencies for the indication of black cells within the aural lines.

5. A Description of the Sub-system of Caecotron

5.1 The Cameras and the Camera Controller

Caecotron uses two Cohu 3000 series environmental resistant television cameras that are mounted on top of a tripod dolly. These cameras are enclosed within two very rugged cylindrical enclosures, and, except for the optics, are sealed against moisture and dust. As mentioned in earlier chapters, the optics is provided by two 25mm f1.4 lenses. These lenses are focused at about ten feet with the aperatures stopped down to provide two pictures that are fairly well focused from a few feet in front of the cameras to a point at infinity.

The control signals and power required to drive the cameras are provided by a Cohu 3900 series camera controller which sits on a platform on top of the dolly. The controller synchronizes the two television cameras to the same clock signal and also provides the rest of the system with the 31.5 kHz basic clock as well as the horizontal and vertical synchronization signals. Higher frequency control signals necessary for the processing of the video signals are generated and synchronized to these signals from the camera controllers.

A block diagram of this subsystem is shown in Figure 12.

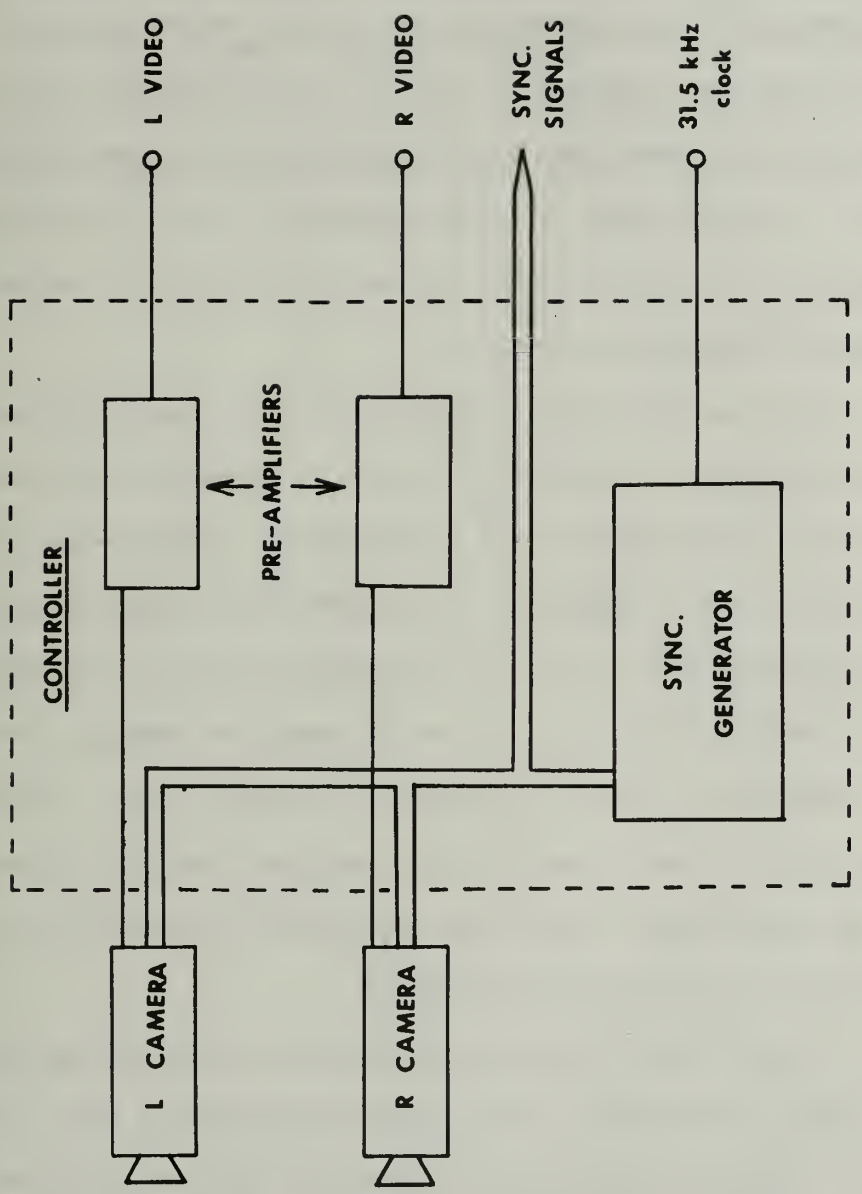


Figure 12. Block Diagram of Camera Controller

5.2 High Frequency Clock Generator

The reason why the 31.5 kHz clock from the camera controller is used as the basic system clock in Caecotron is that the operation of the system has to be in synchronization with the video signals coming from the two cameras. However, a clock of this frequency is not adequate because some of the operations of Caecotron have to be performed at a much higher rate. A good example of such operations is the integration of the video signals in the generation of the matrix pictures. A higher frequency clock signal is therefore necessary.

A step variable high frequency clock is chosen for Caecotron. In the actual system, the period of the high frequency clock is dertermined by the duration of the matrix cell of the matrix picture; and, since the duration of the cell is dependent on the particular magnification that the system is operating under, this high frequency clock is necessarily dependent on the magnification too. In the X1 case, for example, the clock period is chosen to be 1/26 th of that of the video line. 20 of the 26 equal time slots of the video line are therefore situated so that they mark off the cell periods, while the remaining 6 time slots are taken up by the horizontal synchronization signals.

In the X2 case, however, the cells are only half as wide as those in the X1 case and therefore, the clock frequency has to be correspondingly higher. The horizontal line is subdivided into 52 equal periods and again, 20 of them are used in the cell matrix. The same rule applies for the X3 case, where 20 of the 104 time slots of the video line are used. This means that in the X3 magnification case, a high frequency clock signal

of 1.84 MHz is required.

To generate these clocking signals, a phase-lock loop is utilized in the frequency multiplier mode (i.e., with dividers in the feedback loop) to obtain clock signals of 409.5 kHz, 819 kHz and 1.84 MHz respectively for the X1, X2 and X3 modes of magnification. A block diagram of this subsystem is shown in Figure 13. The small table to the bottom left of the figure shows the appropriate periods (T) of the clock signals.

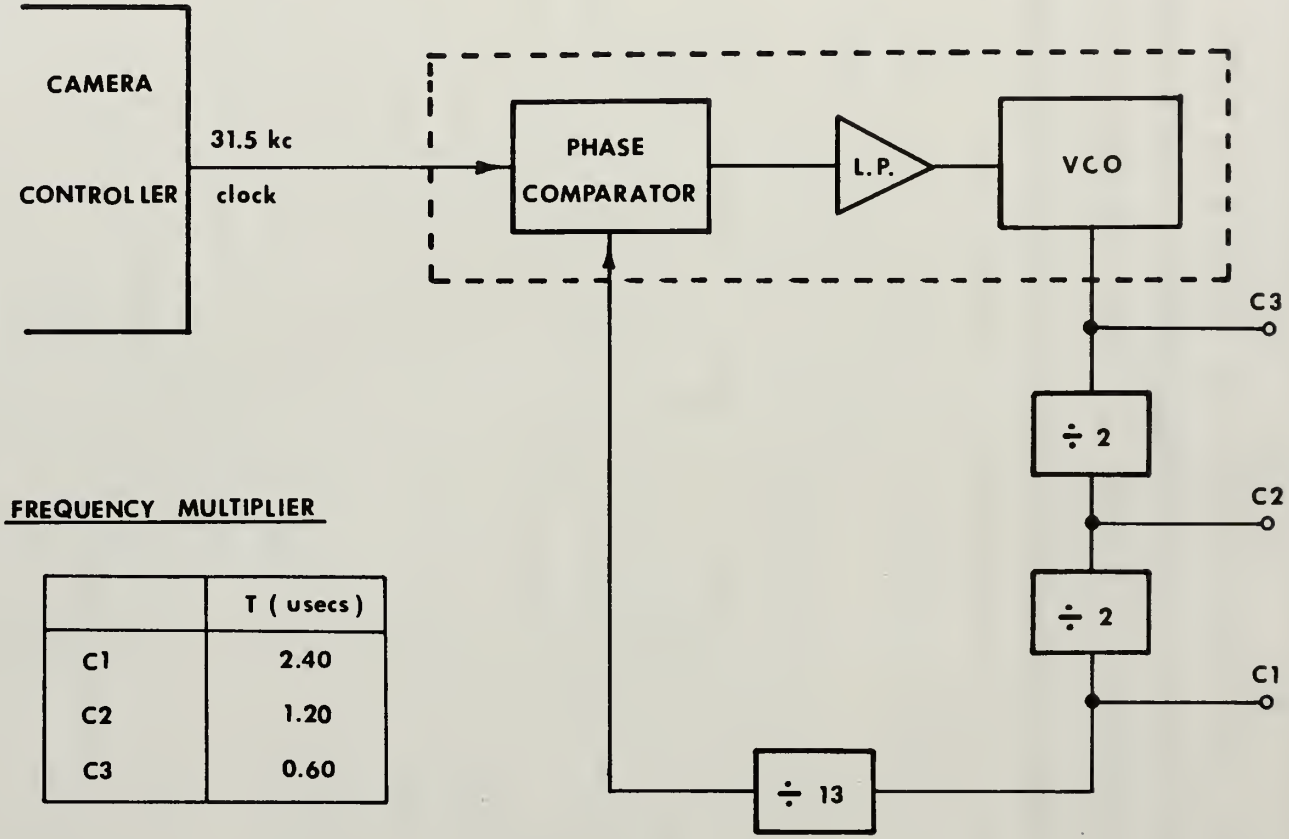


Figure 13. High Frequency Clock Generator

5.3 The Input Video Signal Conditioning Circuit

The input signal conditioning circuit is situated before the line and the cell integrators and its function is to reduce the video signals from the television cameras into standard form to suit the gain factor designed into the integrators. In addition to this, the circuit also serves the function of setting a reference 'black' level for the integrators: This means that the input signal conditioning circuit has to clip off the synchronization signals inherent in the composite video signals from the cameras, and, what is more, set the DC level of the signal that goes on to the integrators.

The line and cell integrators of Caecotron are designed to receive a video signal that is about 1 volt in magnitude referenced to DC ground. The input signal conditioning circuit, therefore, accepts a fairly constant signal (in the long term) from the camera preamplifiers and adjust the video signals to the sepcifications set forth above.

A block diagram of this circuit is shown in Figure 14. It is a fairly simple precise-diode circuit. If the two diodes are removed from the system, the circuit acts simply as an inverting amplifier when the video signal is fed into the inverting input through a resistor. The feedback resistor determines the gain of the amplifier, while the potentiometer associated with the non-inverting input determines the DC level of the output signal. With the two diodes in place, however, the output signal is clamped to a fixed level whenever the output of the operational amplifier goes above this level. When the input video signal goes below this DC level, however, D2 conducts while diode D1 is blocked, and

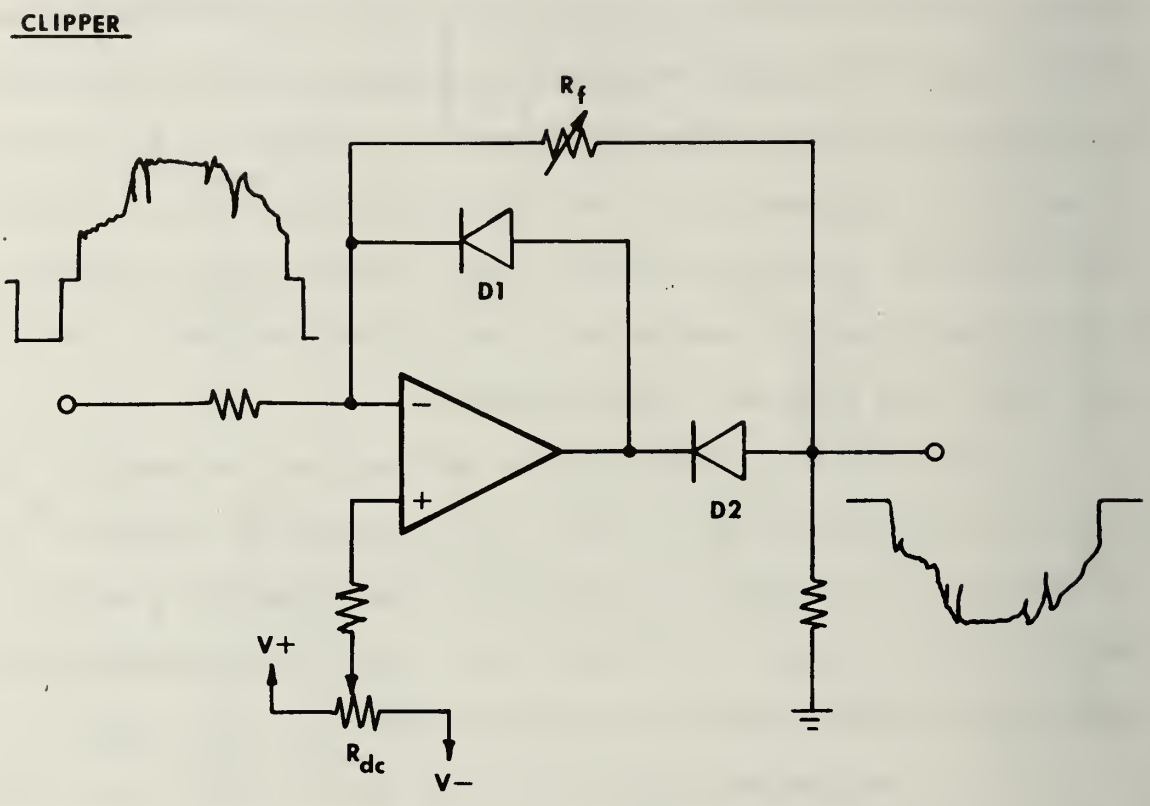


Figure 14. Input Video Signal Conditioning Circuit

consequently, the gain of the output signal is determined by the ratio of the feedback and the input resistors.

5.4 The Line and Cell Integrators

In the preceeding chapter, it was mentioned that the integral of the previous video line is used as a reference in the following line to determine the whiteness or blackness of the cells. For this reason, two integrators ------ the line and the cell integrators ------ are required for each of the two video signals. A block diagram of a line integrator is shown in Figure 15, while a cell integrator is shown in Figure 16.

The line and cell integrators make use of the fairly standard active RC integrators with the capacitor in the feedback path of an amplifier. The resistor and the input signal generate the current to charge the capacitor.

It can be seen from Figures 15 and 16 that both integrators have the same configuration. The only difference between the two is that the time constant of the line integrators is larger than that of the cell integrators, essentially because of the fact that the former has to integrate over a longer period of time. In order to discharge the integrators to their initial states, namely OV, a switch in the form of an analog gate is placed between the inverting input and the output of the amplifier. When the switch is off, the analog gate exhibits a high impedence, and the integrator starts its operation. At the end of the cell or line integration period, the switch is turned on and the analog gate shorts the output of the amplifier to its input (which is at ground level) and returns the integrator to its initial state.

One problem arises for the case of the cell integrators since the cells in a video line are adjacent to each other and an integrator has

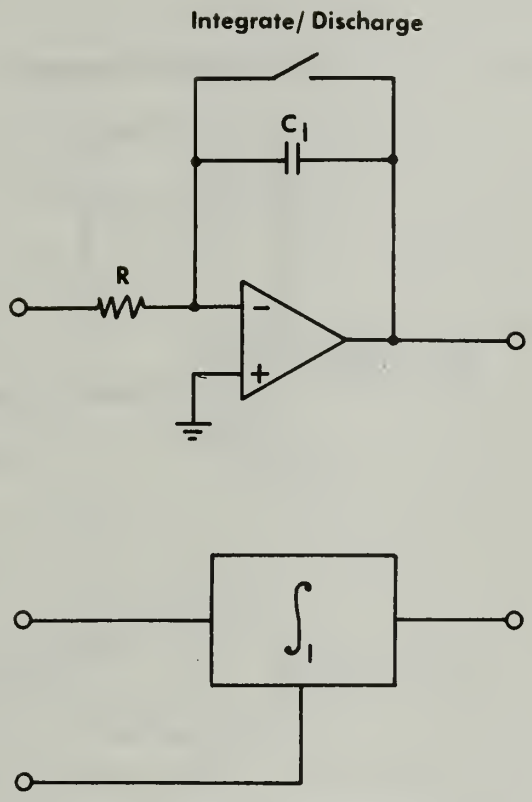


Figure 15. A Line Integrator

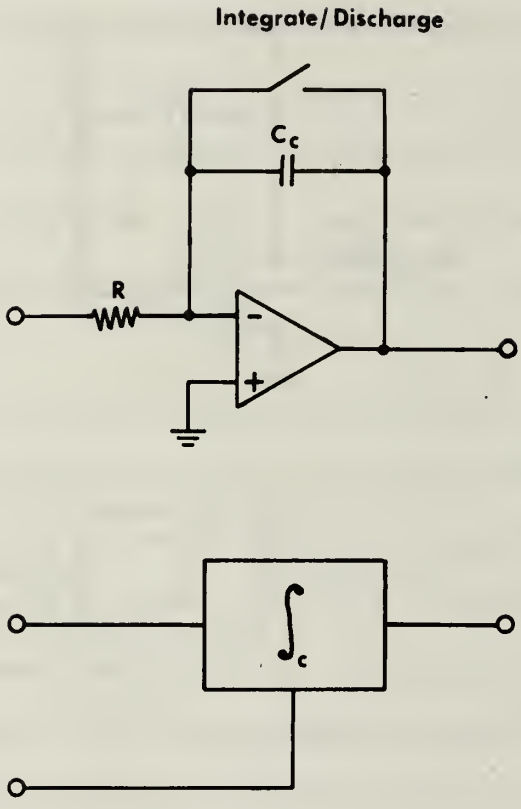


Figure 16. A Cell Integrator

has no time at all to discharge to its initial state before it is required to start integrating the next cell. To get around this difficulty, two identical RC integrators are utilized for the integration of the cells of each video signal. These two integrators integrate and discharge during alternate cell periods so that while one of them is integrating a cell, the other is discharging to its initial state. During the next cell period, their functions are reversed. Their outputs, the integrals of alternate cells, are multiplexed so that the output signal of the integrator that is active is allowed to appear at the output of the multiplexer. A system monitoring the output of the system, therefore, only sees the integration operations of the two integrators, while the discharging process is not observed. A block diagram of the entire cell integration system is shown in Figure 17. The lower portion of the figure shows the control signal that is required for the integrators and the multiplexer together with sample signals at critical locations in the circuit.

The problem that the line integrators have is that their integrals have to be held during the next video line so that they can be used as references for the digitizers, while, in the mean time, these same integrators have to be integrating the video signals of the next line. The obvious answer to this is to use a sample-and-hold circuit that samples the line integral at the termination of the integration period. This sampled signal can then be held for the duration of a video line to retain the reference signal for comparison purposes while the line integrator is freed for integrating the next video line. A block diagram of the line integrator system is shown in Figure 18.

The output of the line integrator is connected to an analog

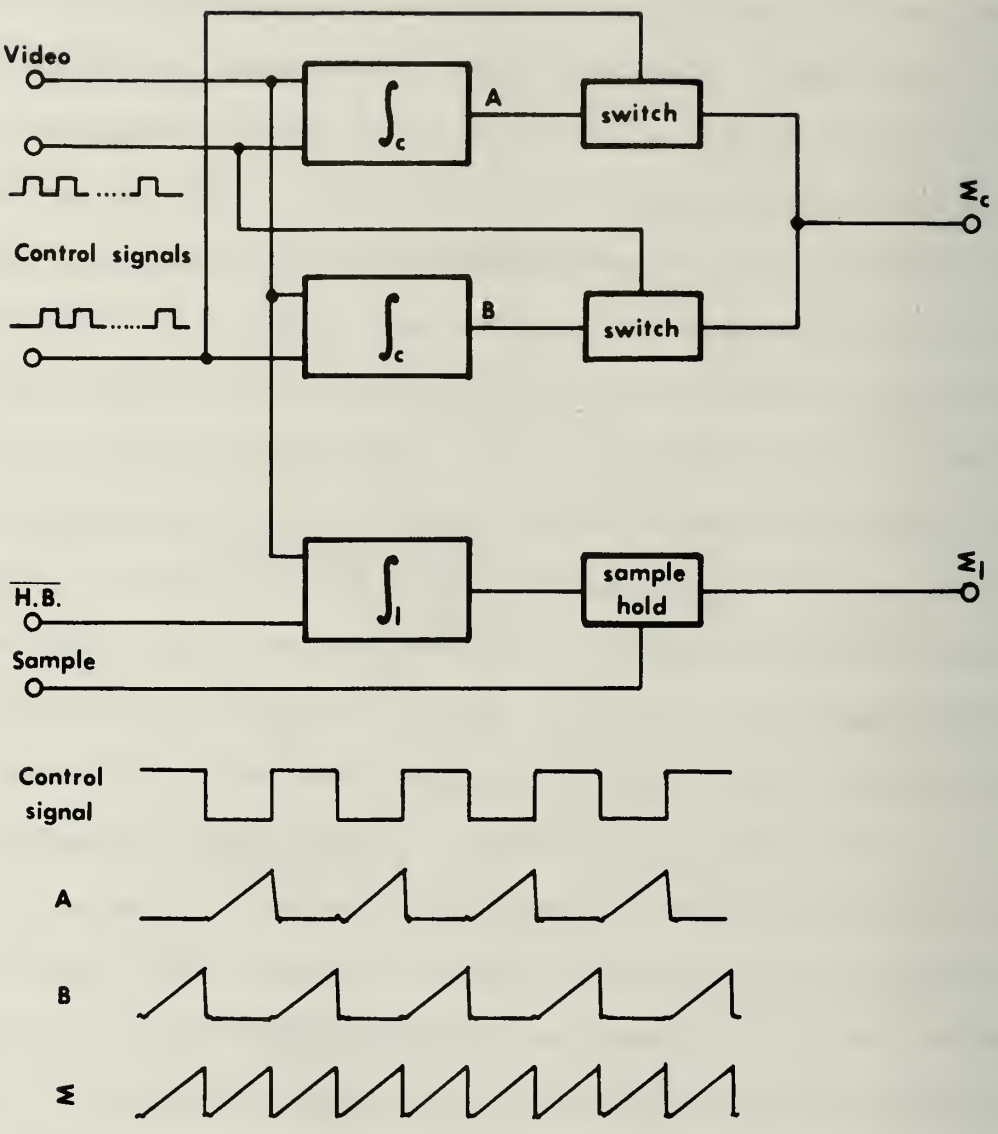


Figure 17. Cell and Line Integrators Block Diagram

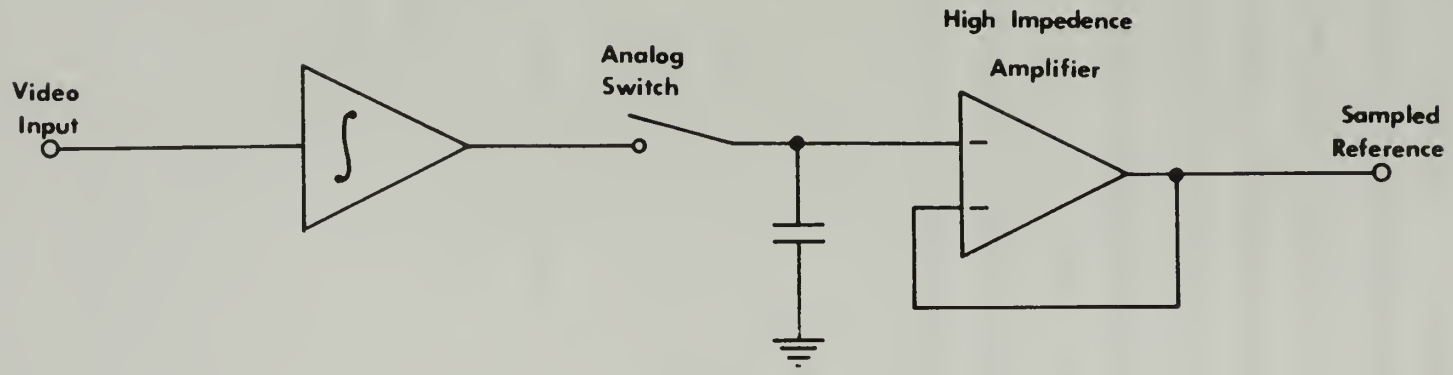


Figure 18. A Line Integrator with Sample-and-Hold Circuit

gate that exhibits a very high impedence (about 10^{12} ohms) when it is off, while having a low impedence (about 10^{2} ohms) when the gate is turned on. The analog gate is connected to a high impedance amplifier (about 10^{12} ohms) operating in the voltage-follower mode with a small capacitor connected to its input. While the analog gate is switched on, the capacitor is charged very rapidly by the signal being sampled because of a relatively small time constant. The output of the amplifier follows the input. After the sampling period, the analog gate is turned off and the sampled signal will be held for the next line period because the stored charge in the capacitor sees a high impedance in the direction of the analog gate and in the direction of the voltage-follower.

5.5 The Controller

The function of this system is to control the line and cell integrators by supplying them with the necessary signals at the appropriate times. It decides where during a television field the first matrix line should start, and when during a video line the matrix cell should begin. It also sets the number of video lines that make up a matrix line and supplies the integration system with all these information in the correct form.

Though the start of the integration process is in synchronization with the vertical drive signal, the amount of delay between the vertical drive signal and the beginning of the first matrix line is dependent on the magnification that the system is working under. In the X1 case, for example, the matrix picture has to include the entire television field and, therefore, integration of the video signal has to commence almost immediately with the termination of the vertical synchronization signal. There exists a slight problem, however, in that the television field begins with a half-line on alternate fields and provisions have to be made so that integration does not begin on such a half-line. As shown in Figure 19, the integration process in the X1 case starts 50 microseconds after the passing of the vertical drive signal. Since the controller is designed so that the first matrix line begins with the horizontal synchronization signal after this 50 microsecond delay, it is ensured that integration always starts on the 3rd line of every field, whether the latter is odd oreven.

In the X2 case, the matrix picture includes only the center 1/4

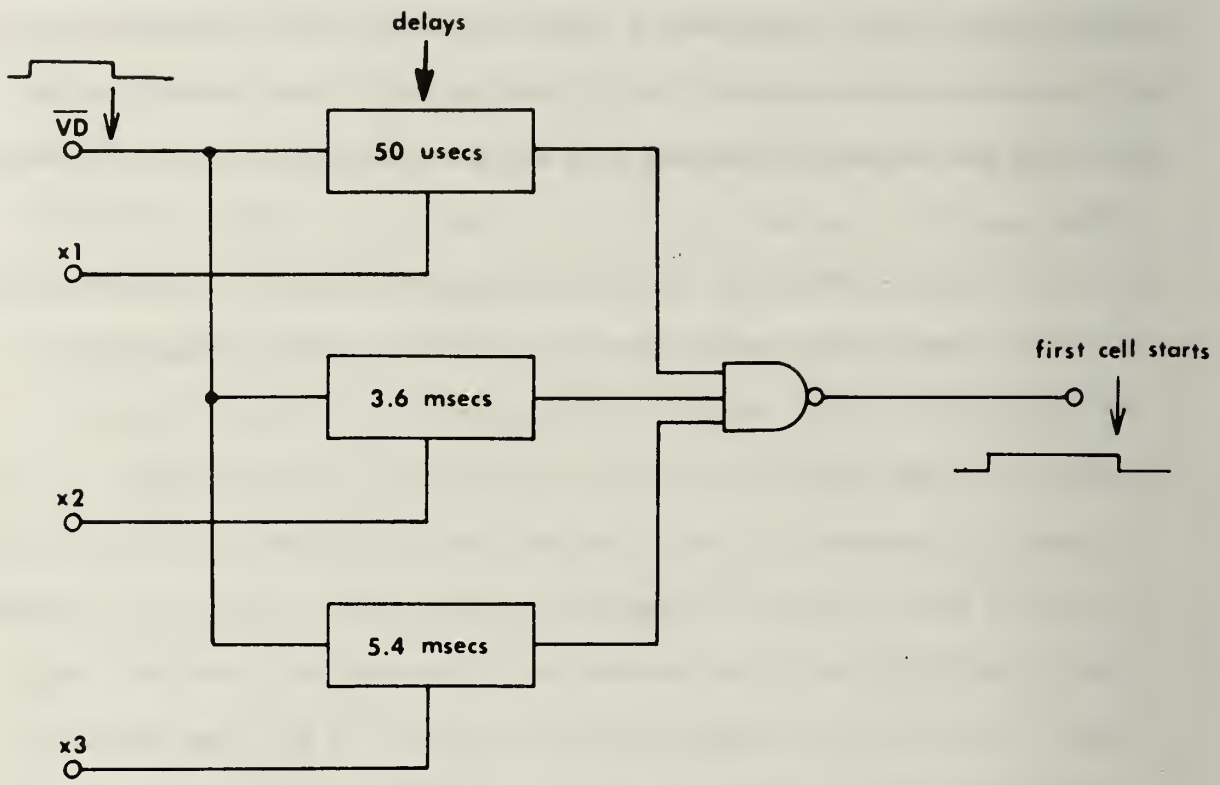


Figure 19. First Line Starting Point Controller

of the video field and, therefore, integration should not begin until the video signal has moved 1/4 of the way down the television field. Again as indicated in Figure 19, integration in the X2 case commences 3.6 milliseconds after the completion of the vertical drive signal.

In the X3 case, the matrix picture consists of 1/16 of the television field. Integration therefore begins 3/8 of the way down the field, i.e. 5.4 milliseconds after the passing of the vertical drive signal.

The location of the first cell of each matrix line is also dependent on the magnification desired. In the X1 case, for example, integration can begin right after the horizontal synchronization signal since the matrix picture covers the entire video field. As shown in Figure 20, this is indeed the case. The slowest clock signal, 409.5 kHz is allowed to count up the horizontal controller divide-by-20 counter which divides the horizontal line into 20 equal intervals corresponding to the 20 cells of the left matrix line. In the X2 case, only the center 1/4 of the picture area is considered and so the first cell of the matrix line does not begin until 12 microseconds after the end of the horizontal synchronization period, i.e. about one quarter of the way down a television line. Similarly, in the X3 case, the first cell starts 18 microseconds after the beginning of the video line. Notice however that the clock frequency used in each case depends on the magnification. In the X2 case, a clock frequency of one half the X1 clock is used and, consequently, the cells are only one half the size of those of the X1 case; and similarly, the cells of the X3 case are one half the size of those of the X2 case.

The control signal generated by the circuit in Figure 20, labelled '21 pulses', is, in reality, a sequence of 21 pulses that delimit

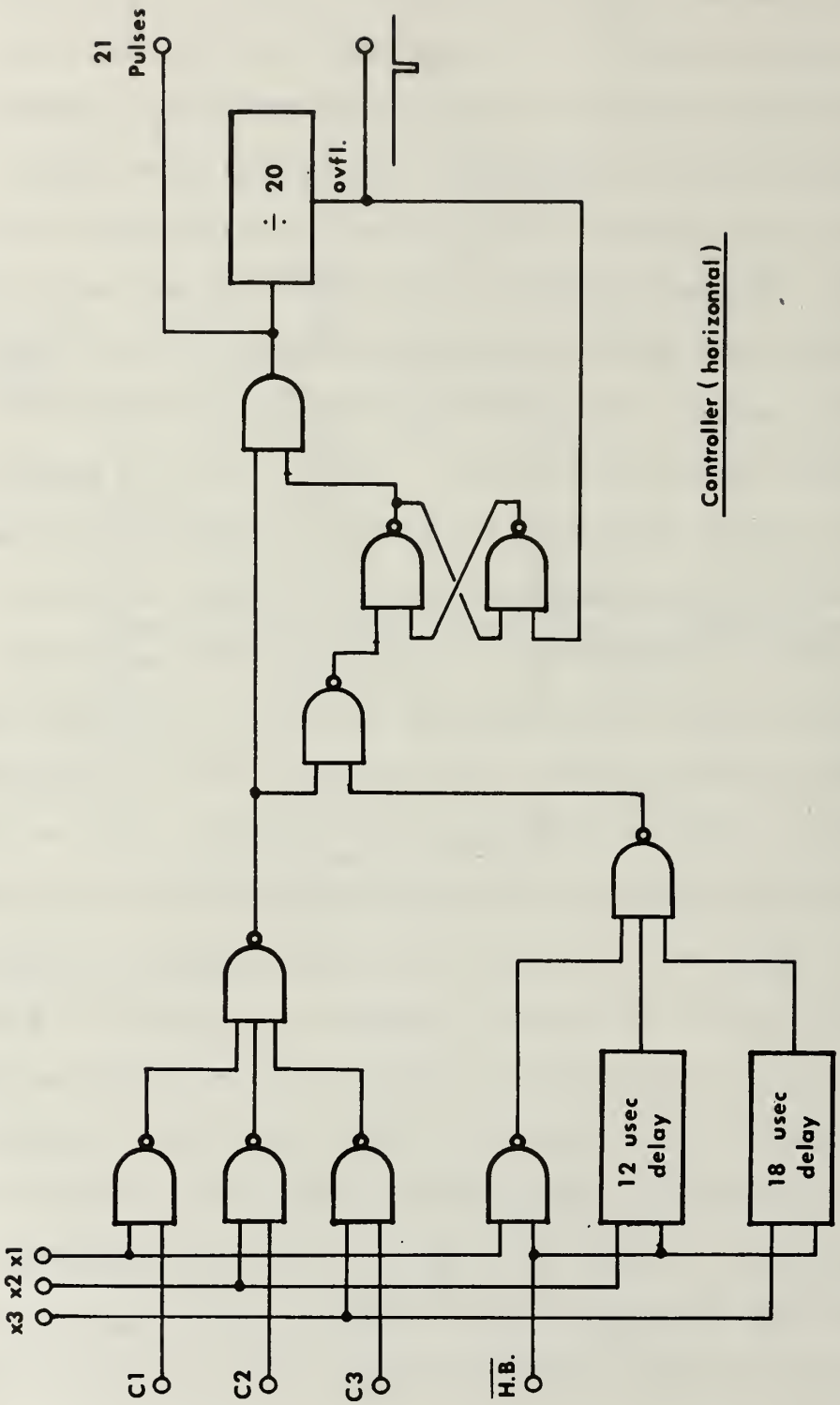


Figure 20. The Horizontal Controller

the 20 (or in the case of the right-hand picture, 16) cells of each video line being integrated. The first pulse of this signal, therefore, corresponds to the start of the first cell in the line, and the 21st pulse indicates the termination of the last cell. The two flip-flops in Figure 21 reduce this signal into the two cell integration control signals shown near the top of the figure. Since the integrators were designed so that they integrate when the control lines are high, these two control signals cause each of the two cell integrators associated with either the left or the right video signal integrators to integrate and discharge alternately; and, as described in an earlier section, their outputs are multiplexed to obtain the signals corresponding to the integrals of the cells.

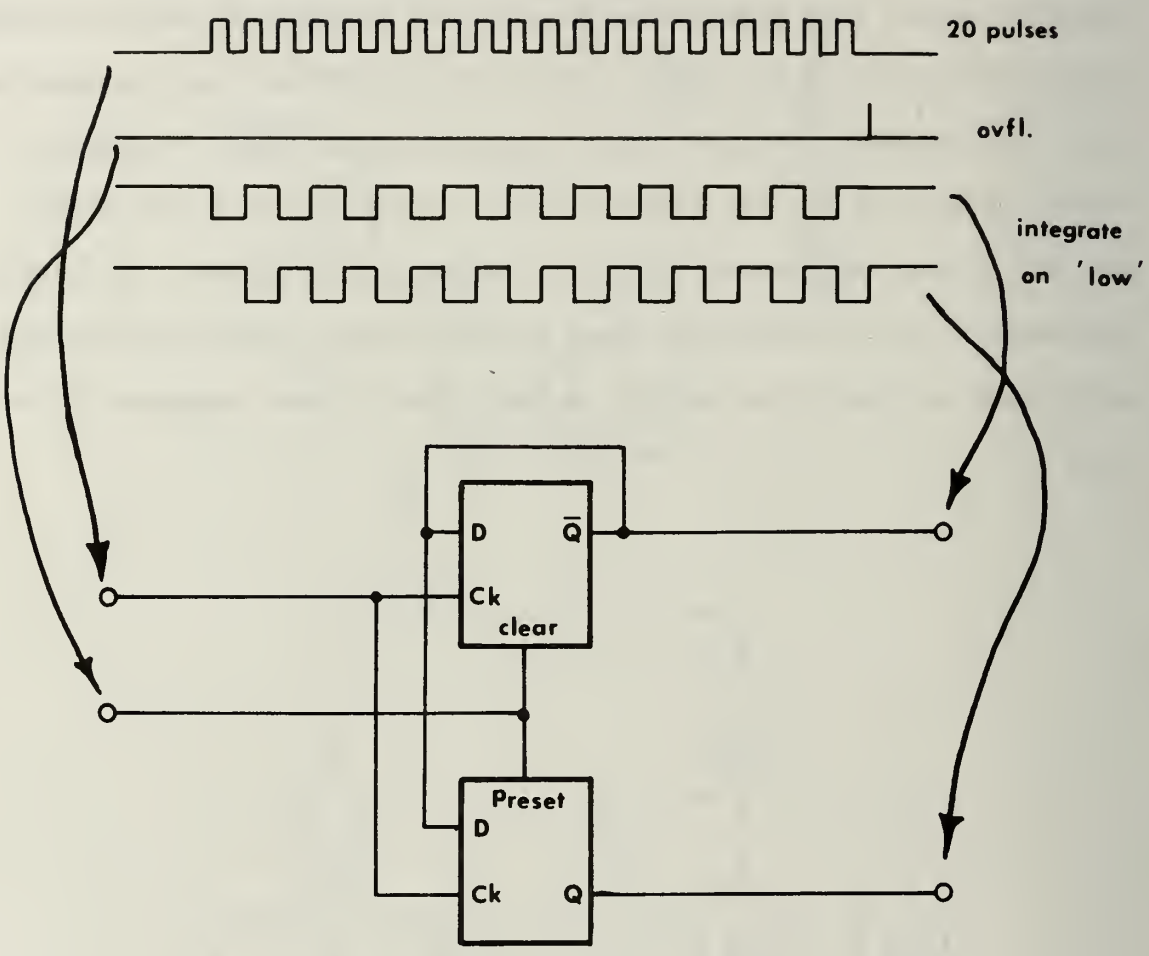


Figure 21. Integrators Control Signals

5.6 The Processor

In Chapter 3, a description was made on the telemetry of Caecotron. It was mentioned how a two-camera system can be used in range-finding by comparing different segments of the left camera video signal with the right camera video signals and delayed versions of the latter. The Processor circuits in Caecotron are used in such a rangefinding operation.

The 20 cells of a left matrix line are first of all grouped into 5 segments of 16 cells each. Thus cells 1 through 16 are included in one segment, for example, and so are cells 2 through 17, 3 through 18 and so on. Each of these line segments is compared with the 16-cell right matrix line on a cell to cell basis, using an EXCLUSIVE-OR operation to detect similarities. Since the same 16-cell line of the right picture is used to compare with the five different 16-cell line segments of the left picture, and since no storage is made of the left matrix picture, such a correlation operation can easily be done by on-line comparison of the left matrix picture with the right matrix and the four versions of this right matrix picture that are delayed through shift registers. A block diagram of such an EXCLUSIVE-OR correlator is shown in Figure 22. The right matrix line is shifted into the 5 bit shift registers and from the outputs of the latter we can obtain five time-shifted versions of the right matrix line. Since the shift register is clocked by the system clock, each of these five versions are delayed by 1 cell period from the one preceeding. The left matrix line, consisting of 20 cells, is shifted into a 1 bit shift register and the output of this shift register is fed

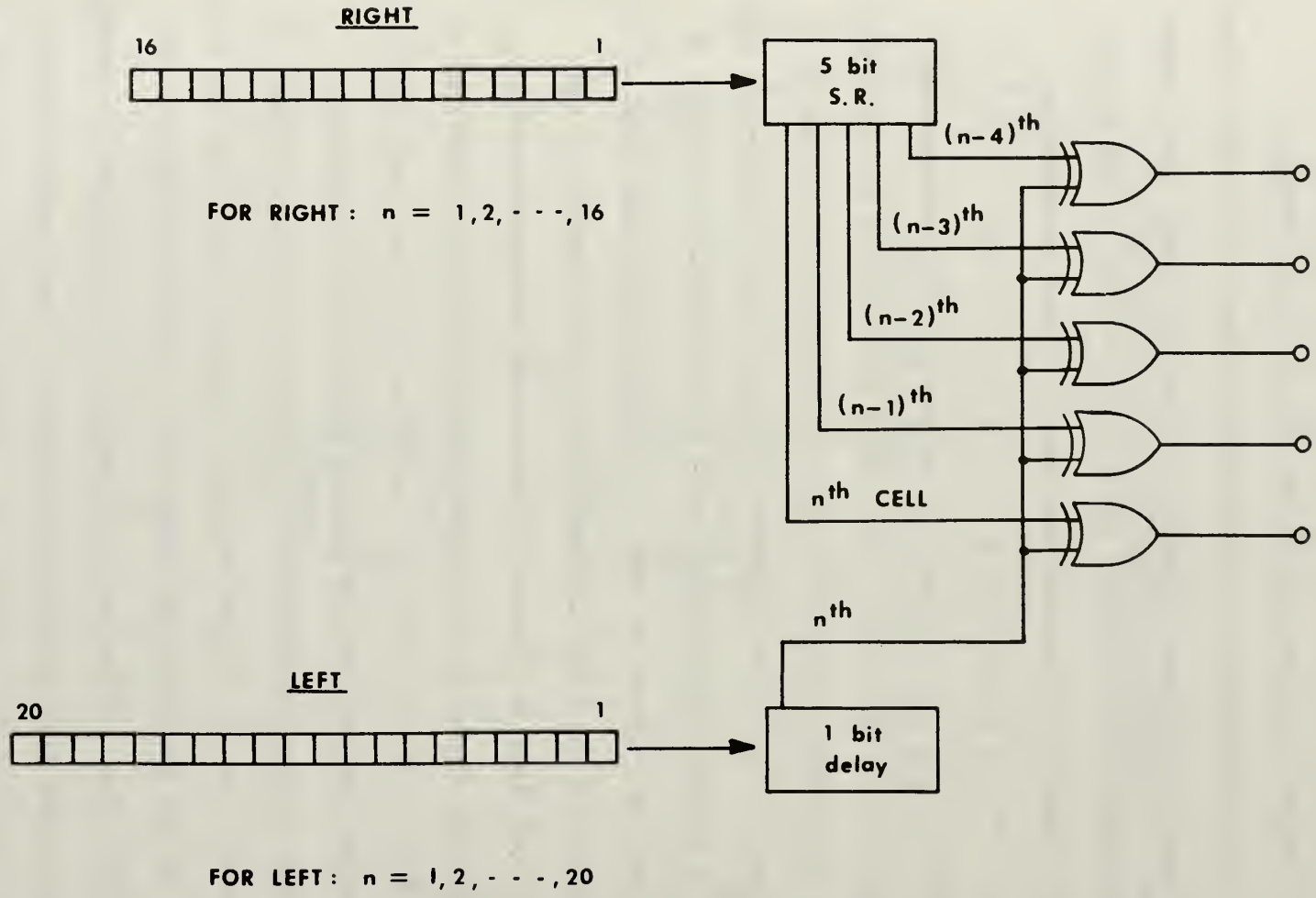


Figure 22. Exclusive-Or Controller

to the other inputs of the EXCLUSIVE-OR gates for comparison with the time shifted copies of the right matrix line. Each time a mismatch exists between two cells, the output of the corresponding EXCLUSIVE-OR gate goes to '1' state and such mismatches can be recorded by using counters at the outputs of the EXCLUSIVE-OR correlators.

Care has to be taken, however, that only matrix cells that are meaningful are compared. In Figure 22, it can be seen that as the first cells of the two matrix lines exit from the shift registers, the n-1, n-2, n-3 and n-4 outputs of the 5 bit shift registers do not contain meaningful information because data has not been shifted into them at that moment. The bottom EXCLUSIVE-OR gate in the column, however, has at its inputs the first cells of the left and right matrix lines and hence its output is valid. During the next clock period, the bottom two gates are valid; and, this continues until all the outputs from the EXCLUSIVE-OR comparators become meaningful. A mask therefore has to be designed so that only valid information is compared by the correlators, while others are masked from the comparison counters. Figure 23 shows the block diagram of such a mask together with its masking signals at the bottom of the figure. Each one of the control signals labelled 'a' through 'e' is used to gate the five EXCLUSIVE-OR outputs of Figure 22; and, since the system is designed so that the masks are 'off' when the control signals are '1', the nth comparator of Figure 22, controlled by signal 'a' in Figure 23, has its correlation process initiated first, and it is also the comparator that has its operation terminated first at the end of the first 16 cel s of each line.

A partial block diagram of the correlator system is shown in

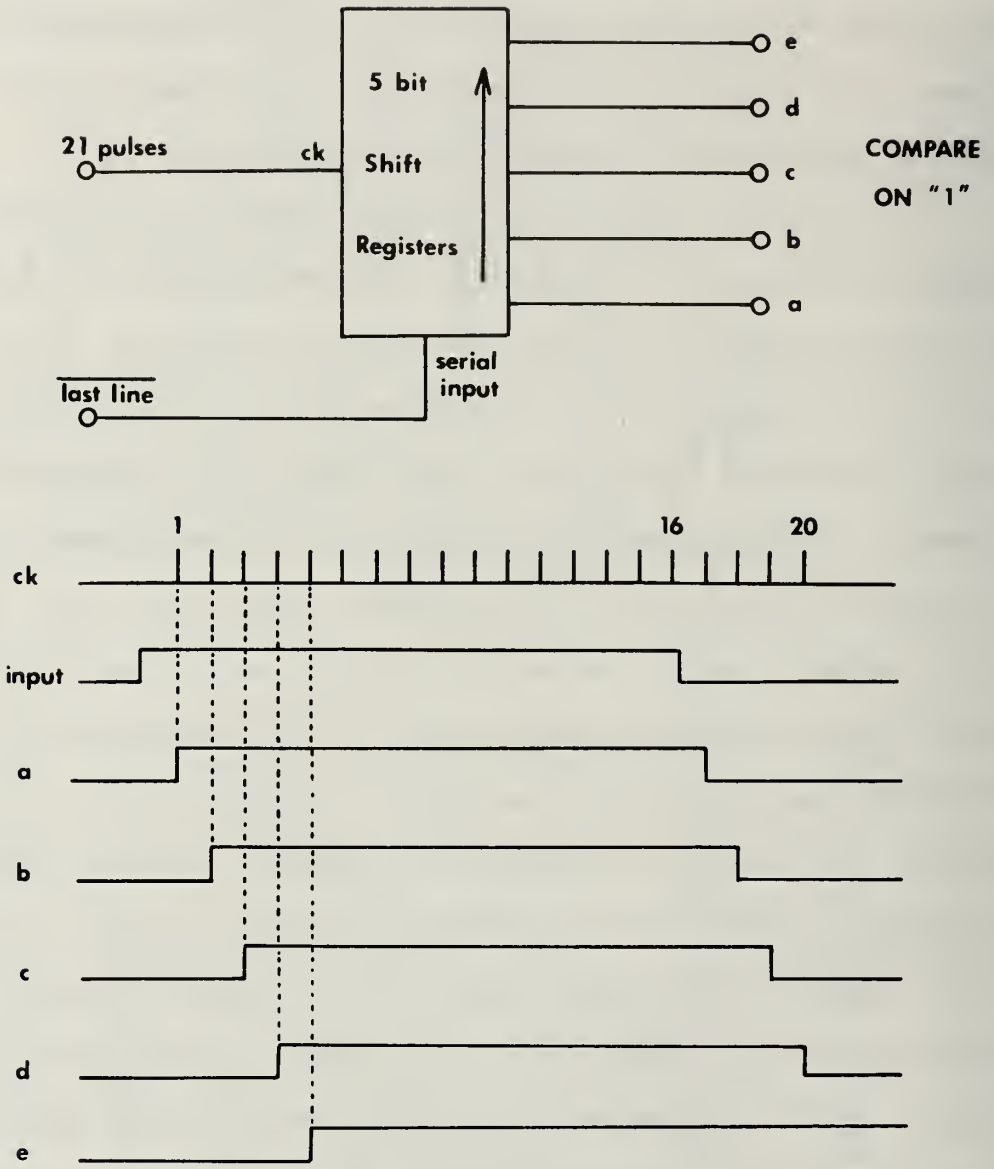


Figure 23. 5-bit Shift Registers used as a Mask

Figure 24. It consists mainly of the circuits of Figure 22 and 23 combined and it also contains some of the timing signals required for the latching and comparison of the information signals. As mentioned earlier, the outputs of the EXCLUSIVE-OR gates are connected to 5 counters that count up the total number of mismatches for each of the segments of the left matrix picture. Again, as described in Chapter 3, the amount of shift of the right picture that gives a minimum amount of mismatched cells at the end of the correlation process gives us the depth information that we are seeking.

The EXCLUSIVE-OR correlators of Figure 24 are connected to the five sets of 8 bit counters in Figure 25. Since the maximum number of dissimilarities between two 16 X 16 matrix pictures does not exceed 256, the 8 bit counters are sufficient under the worst case condition. After the 16 X 16 matrices are compared, the contents of these counters are counted down to zero simultaneouly by the clock; and, the counter that reaches a zero count first (indicating a best fit for that particular picture shift) sets a latch, and the count down process is stopped. The latches are then sampled by the output circuits to determine the amplitude of the output tone sequence.

One word should be mentioned about how the right matrix picture (16 X 16) is stored so that it can be displayed to the user of the system. Since the elements of the 16 X 16 matrix are available serially from the integrators and they are also displayed serially to the user, a 256 bit shift register is used for this purpose. The right matrix picture is stored, cell by cell, into the shift register as it is available. During the playback, the data stored is shifted out serially by a much

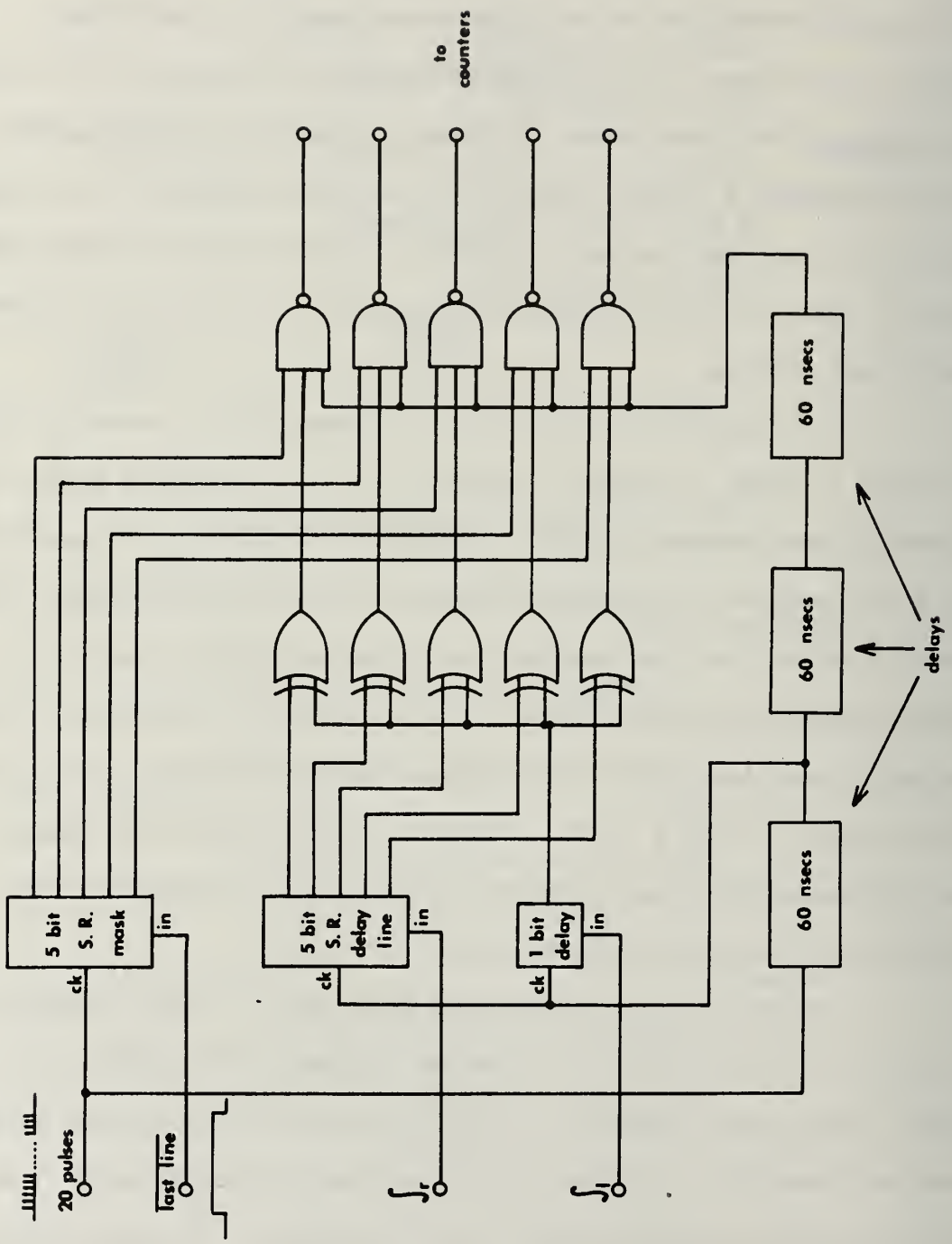


Figure 24. Block Diagram of Correlator

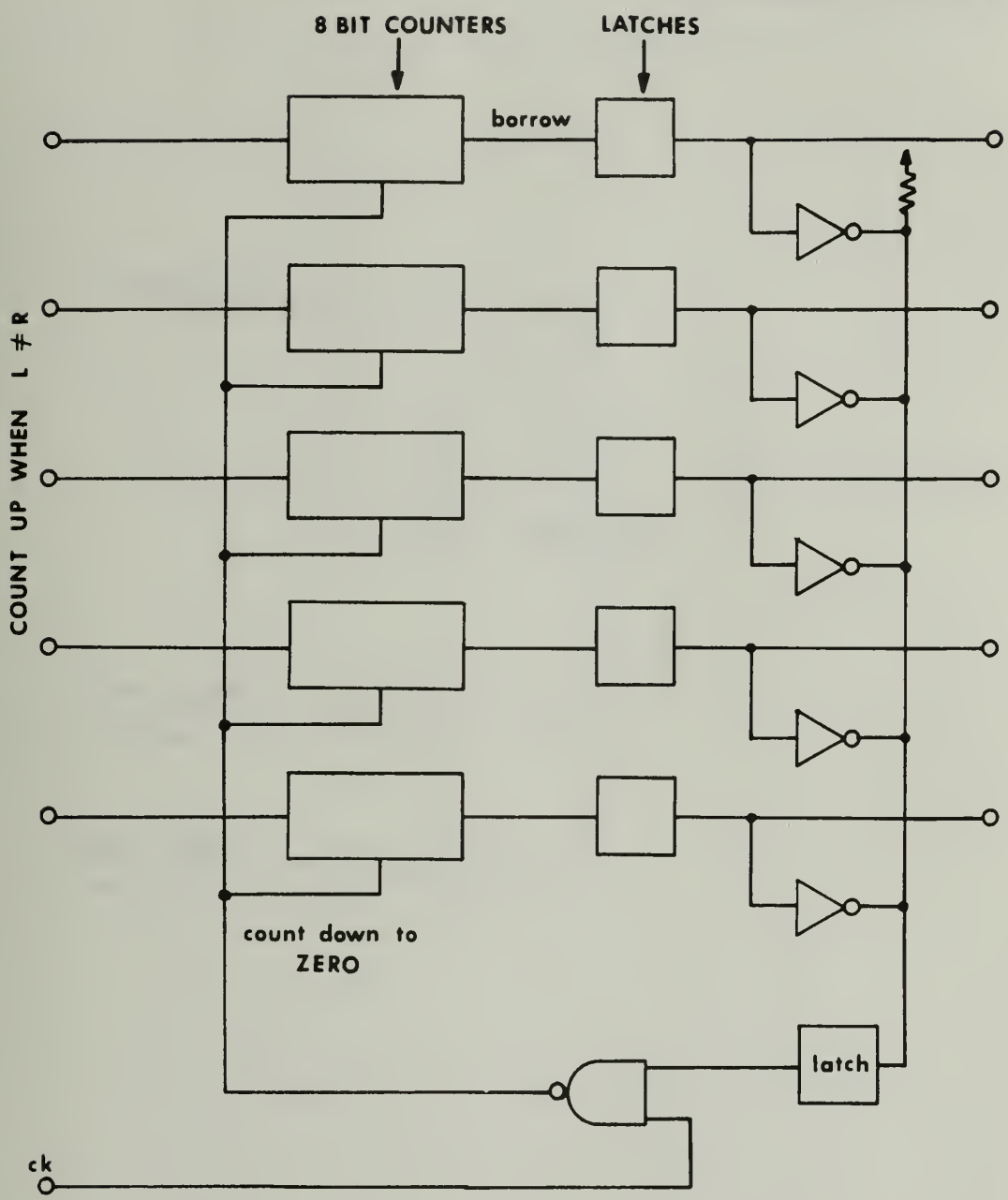


Figure 25. Difference Counters

slower clock signal. A block diagram of this matrix picture memory is shown in Figure 26.

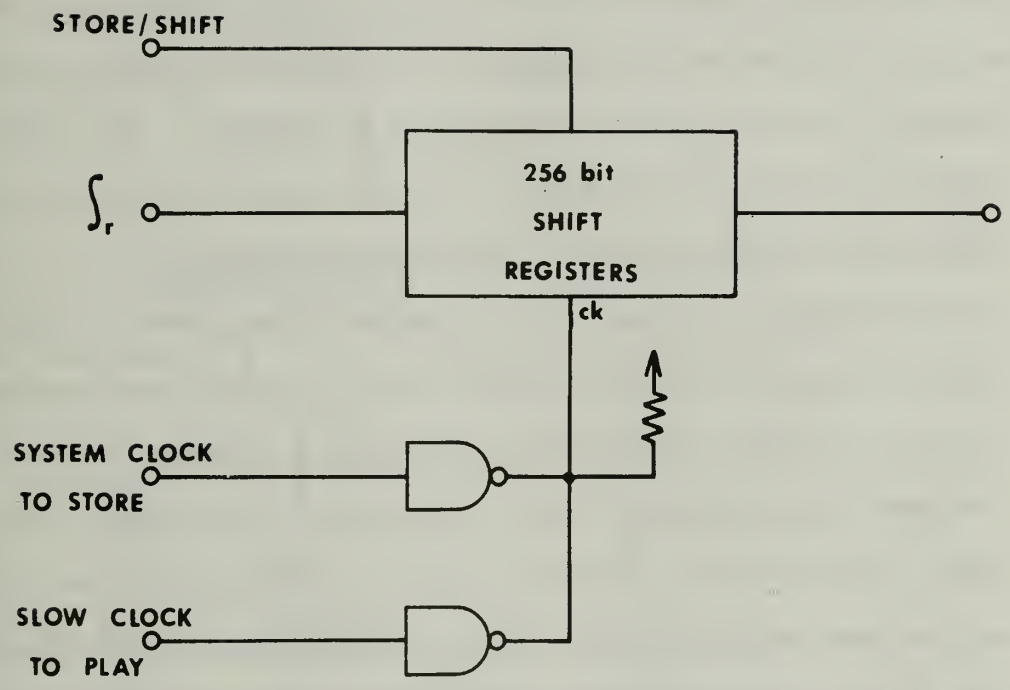


Figure 26. Matrix Picture Memory

5.7 Output Variable Gain Amplifier

Since the output tone sequence displayed to the user can be in one of five loudness levels to indicate depth information, a variable gain amplifier, controlled by the output of the processor, is needed to modulate the 16-step tone sequence. A digital-to-analog converter is designed to serve as such a variable gain amplifier. The inputs of the circuit in Figure 27 is fed by the control signals from the circuit in Figure 25, together with the tone sequence produced by the tone generators. If, for example, an object is at distance D0 away from the user (i.e. fairly far away), D0 is at a high level, while the other control signals are at a low level, and the digital-to-analog converter puts out a fairly low level tone sequence. On the other hand, if D1 is high, then the 2^1 input, as well as the 2^0 input to the D/A converter will be switched low, and the tone sequence at the output of the system will be twice the amplitude of that in the D0 case. Note moreover that D4 has priority over D3, which also has priority over D2 and so on. This means that if the system has both D4 and D1 at a high level, then the louder tone signal corresponsing to D4 is displayed to indicate that an object is at close range.

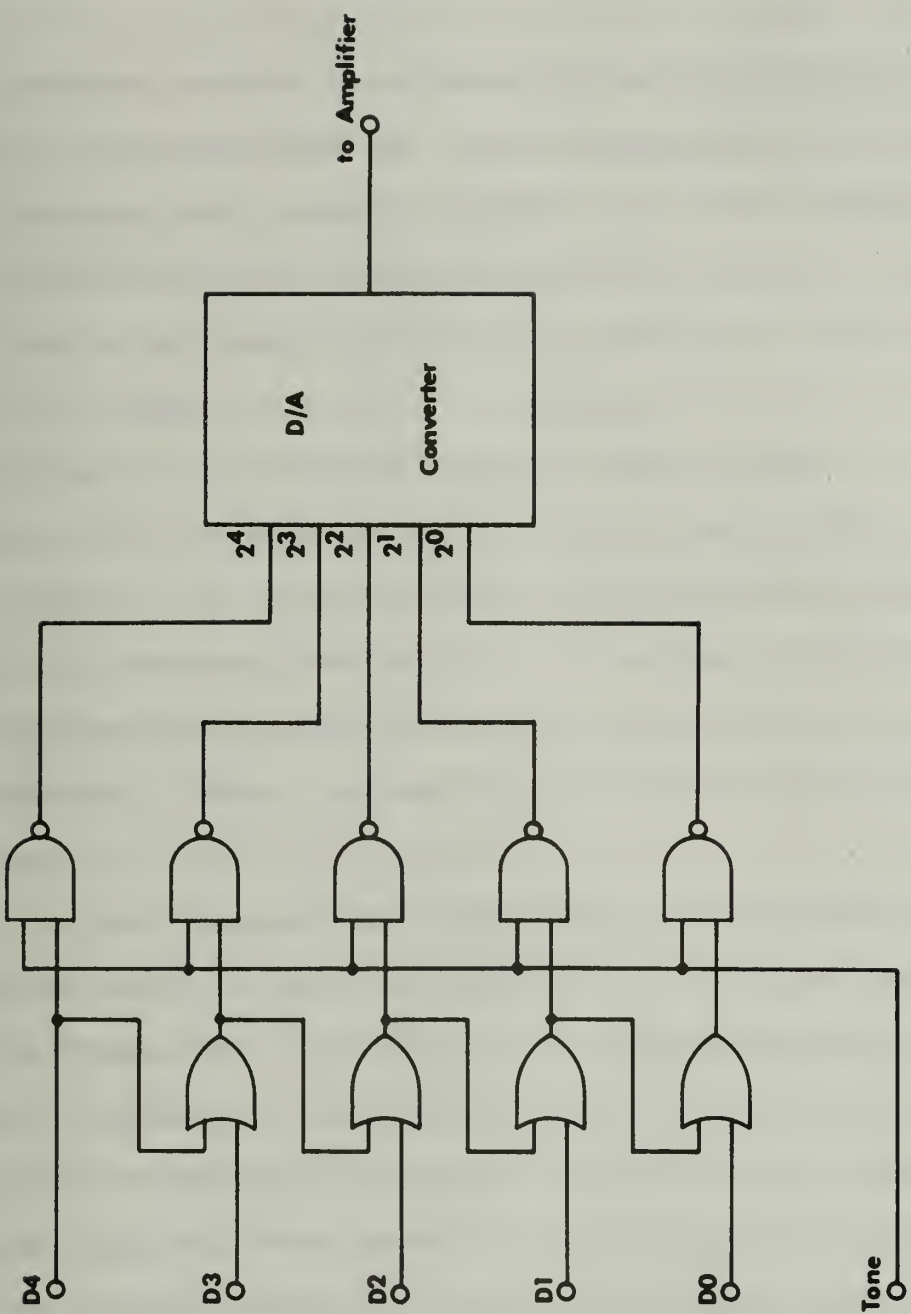


Figure 27. D/A Converter used as a Variable Gain Amplifier

6. Alternate Approaches to the Implementation of Caecotron

A study was made on the feasibility of using an integrated microprocessor as a general controller of the whole system since, if this was possible, most of the attractive features of the integrated microprocessor (low power, programmability, etc.) would be ideal for Caecotron. Such a controller can supervise the acquisition and reduction of data from the television cameras as well as the processing of the two reduced matrix pictures. However, a study of the microprocessors that are available off-the-shelf reveals that none of them are really fast enough for that purpose. The Intel 8080, for example, has a minimum instruction cycle of 2 microseconds, while for most instructions, the cycle time is in excess of this. On the other hand, the minimum clock period for Caecotron in the X3 magnification case is under 1 microsecond.

Despite this, an integrated microprocess can still be considered in the implementation of the processor section of the machine since the processing time of the acquired data, namely the two matrix pictures, is not critical and, in any case, is not significant when compared to the relatively long play-back time of the 16-step tone sequence. However, a careful analysis of the procedure involved in the processing of the matrix pictures shows that the use of a microprocessor for this function alone is not really cost effective. This is due to the fact that the acquired data cannot be operated on on-line because of the insufficient speed of the microprocessor and consequently additional memory and a significant amount of circuitry has to be introduced.

As the faster bipolar microprocessors become more readily available

their usage in a system like Caecotron would be more attractive.

A block diagram of a possible system using a microprocessor to perform the processing of the acquired data ia shown in Figure 28. The microprocessor used in the design is the Intel 8008 which is cheaper (about 1/3 as much) than the Intel 8080 but has all the functions that the correlation procedure requires. Since the information on the two matrix pictures are available from the vertical integrators serially, and, what is more important, because the data can be called and operated on by the processor serially in the same manner, the two 16 X 16 and 16 X 20 matrix pictures can be stored in shift registers. These shift registers have configurations of 8 X 32 and 8 X 40 so that each word (of 8 bits) holds the information of half a column of the respective right and left matrix pictures. The processor can, therefore, accesss one word each from the two shift registers at a time for the comparison process and, in effect, compares the two matrix pictures serially by column.

The procedure of the comparison process as outlined previously can be stored in the Read-Only-Memory, while a few additional words of random-access-memories are necessary for storing the temporary results of the correlation process. The multiplexers are necessary for switching the data to the appropriate locations and for the proper timing of input to and output from the microprocessor since the 8008 has a common input-output data and address bus. The controls contain nothing more than decoder networds that switch the data to the appropriate locations at the proper times.

This is a relatively inexpensive system compared to most

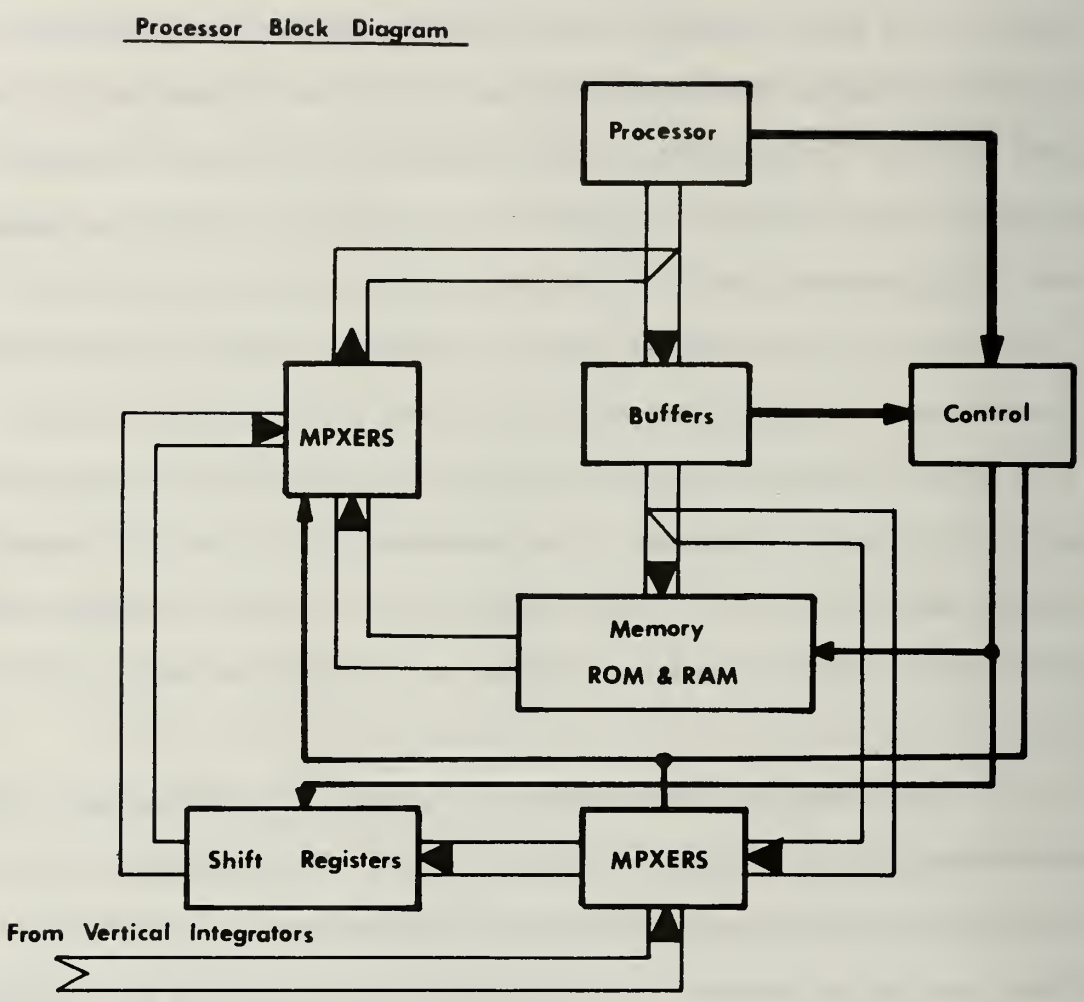


Figure 28. Block Diagram of a Possible Microprocessor Controller

microprocessor systems because of the relatively simple demands of the correlation process. Most of the outlay is in the microprocess and read-only-memory, which, at the present, cost about $200 in single quantities. It is especially attractive if the microprocessor is fast enough for the other control functions of Caecotron, since such a system would be essentially the same as the configuration as the block diagram of Figure 28, though a somewhat more elaborate control system is necessary to control the integrators.

Recently, a few semiconductor manufacturers have announced bipolar versions of microprocessors which are 10 to 15 times faster than the corresponding MOS versions. The 3000 series of computing elements announced by Intel, for example, have an add time of 125 microseconds, and what is more, can be designed to have a 16 bit word length. Such a product is doubtlessly fast enough for application in the control of the cell integration process, and, because of the 16 bit word length, is ideal for the processing of the 16 cell columns of the matrix pictures. Such a system costs quite a bit more: At the time of this writing, a 16 bit word processor costs in the order of $700 in single quantities. Still this is a very attractive approach to the problem because of the virtues (low power, compactness and programmability) of the microprocessor.

Yet another approach to the implementation is this: Instead of using two television cameras to acquire the matrix pictures, two photodiode arrays can be used. This dispenses of the use of cell and line integrators described previously to generate the matrix pictures, since integration is done directly on the photodiode arrays. Two analog delay lines in the form of charge-coupled devices (CCD) can be used to shift out the contents

of the phtodiode arrays and the analog (!!) contents of the photodiodes can be compared using analog comparators. These operations can, of course, be controlled by a microprocessor of the sort similar to the Intel 8008 since speed is not the problem. Such a system is almost ideal since the photodiode cameras are much more compact than the vidicon cameras, and, what is more, significantly simplify the operation of Caecotron. The disadvantage of such a system however, is that it is significantly more expensive: A 50 X 50 photodiode array together with the CCD, for example, costs in excess of $1500 each! It is, however, not inconceivable that they will come down in price as they become more widely used, and if that is the case, their use in a Caecotron-like system should be contemplated.

7. Conclusion

The system described in the preceeding pages has been implemented at the Information Engineering Laboratory of the University of Illinois to study the feasibility and usefulness of such a machine. Since the time that Caecotron has become operational, it has been demonstrated to both sighted and unsighted individuals and the results obtained has been very encouraging.

The first introduction that a user obtains on the system is a short explanation of then encoding scheme used in the aural picture: Frequency shifts correspond to brightness variations, while the amplitude modulation of the tone corresponds to the distance of a particular element in the matrix picture. The user is then allowed to use Caecotron to identify tone patterns at a playback rate that is comfortable. After a few minutes' practice, the user can usually identify objects like tall fences, short fences, black vertical stripes on a light background, black boxes in mid-air and diagonal stripes. Again, after some practice, the playback rate can be increased significantly: Most users find the tone sequences intelligible at a playback rate of between 5 to 10 seconds for the 16-step tone pattern.

The next logical step to improve the performance of Caecotron is obviously the miniaturization of the system by using smaller components since the machine, as it now stands, is not really portable. Some of the alternative components suggested in the preceeding chapter will help tremendously in this direction if they can be obtained for use in Caecotron: Miniature cameras using solid-state imaging devices will decrease the bulk of Caecotron by an order of magnitude, and will also decrease its weight by

much more than an order of magnitude since , as described in Chapter 6, the processing of the information will be much simplified.

Appendix

The circuit diagrams included herein contain the working schematics of the main systems that make up Caecotron. The following circuits are included:

1. High Frequency Clock Generator
2. Integrator Controller
3. Cell-line Controller
4. Cell Integrators
5. Line Integrators
6. Cell Integrators and Multiplexers
7. Video Amplifiers, Line Integrators and Sample-and-Hold Circuits
8. Processor #1
9. Processor #2
10. Tone Generator
11. Output Amplifier and Level Controller
12 Output Control Circuits

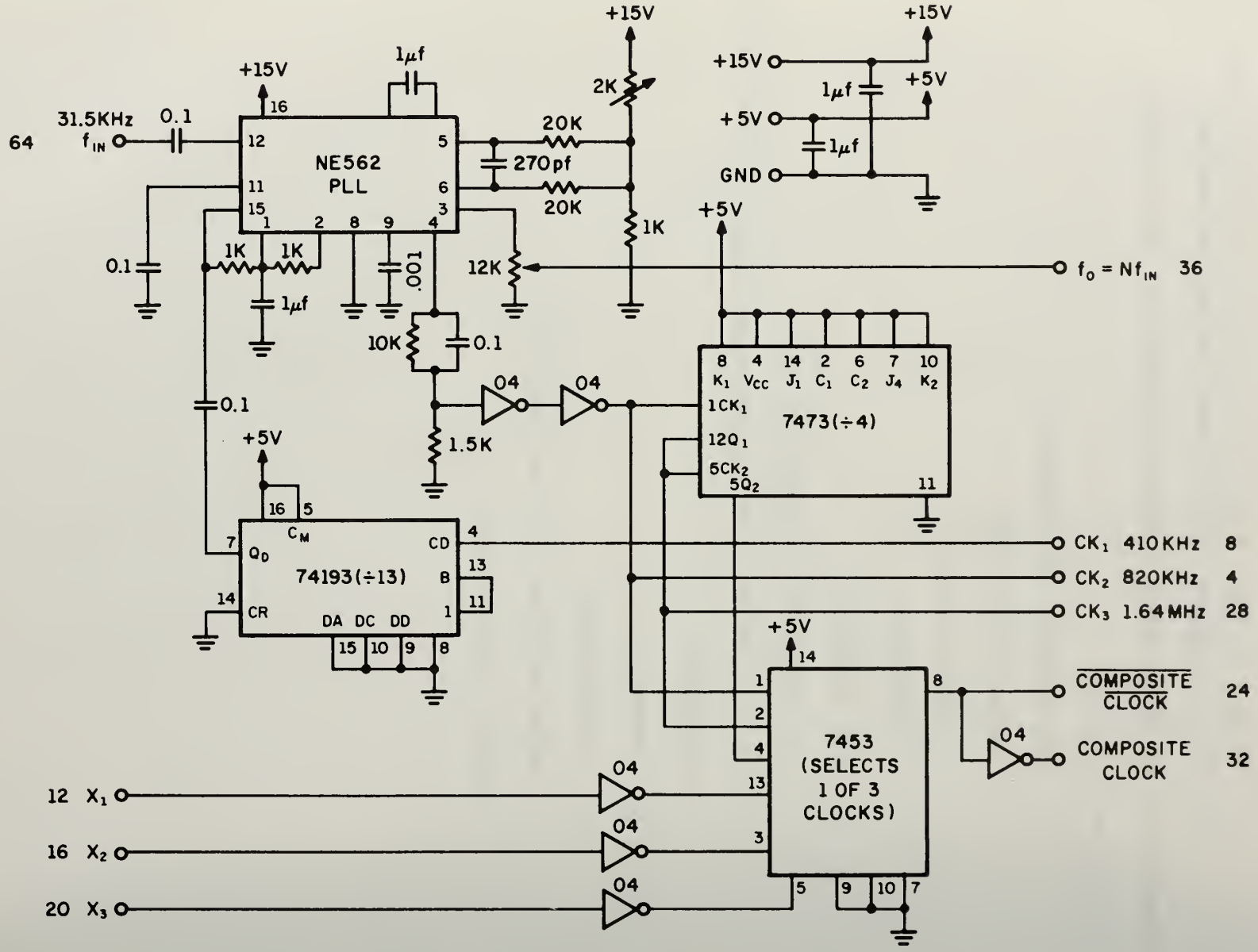


Figure A1. High Frequency Clock Generator

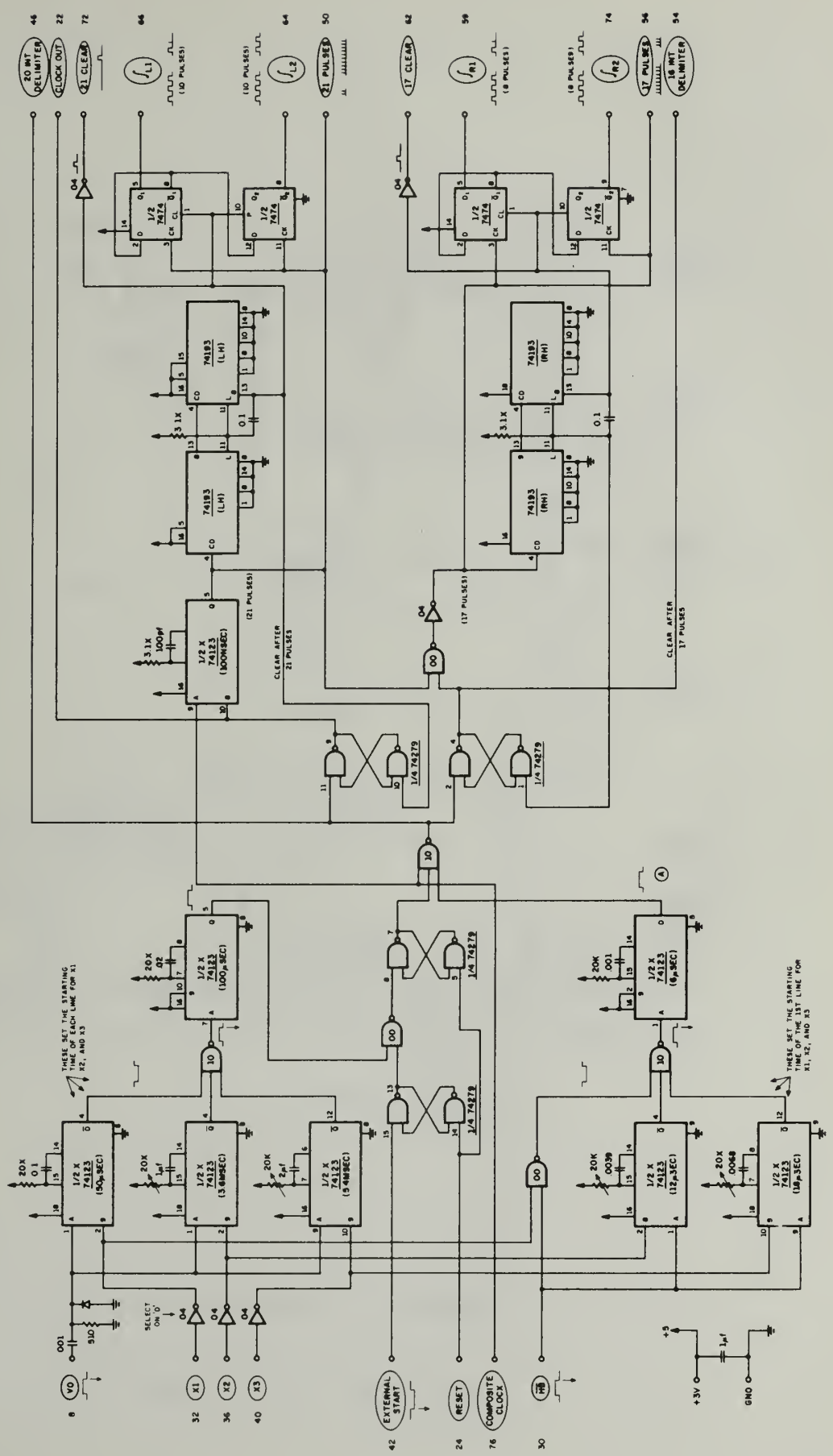


Figure A2. Integrator Controller

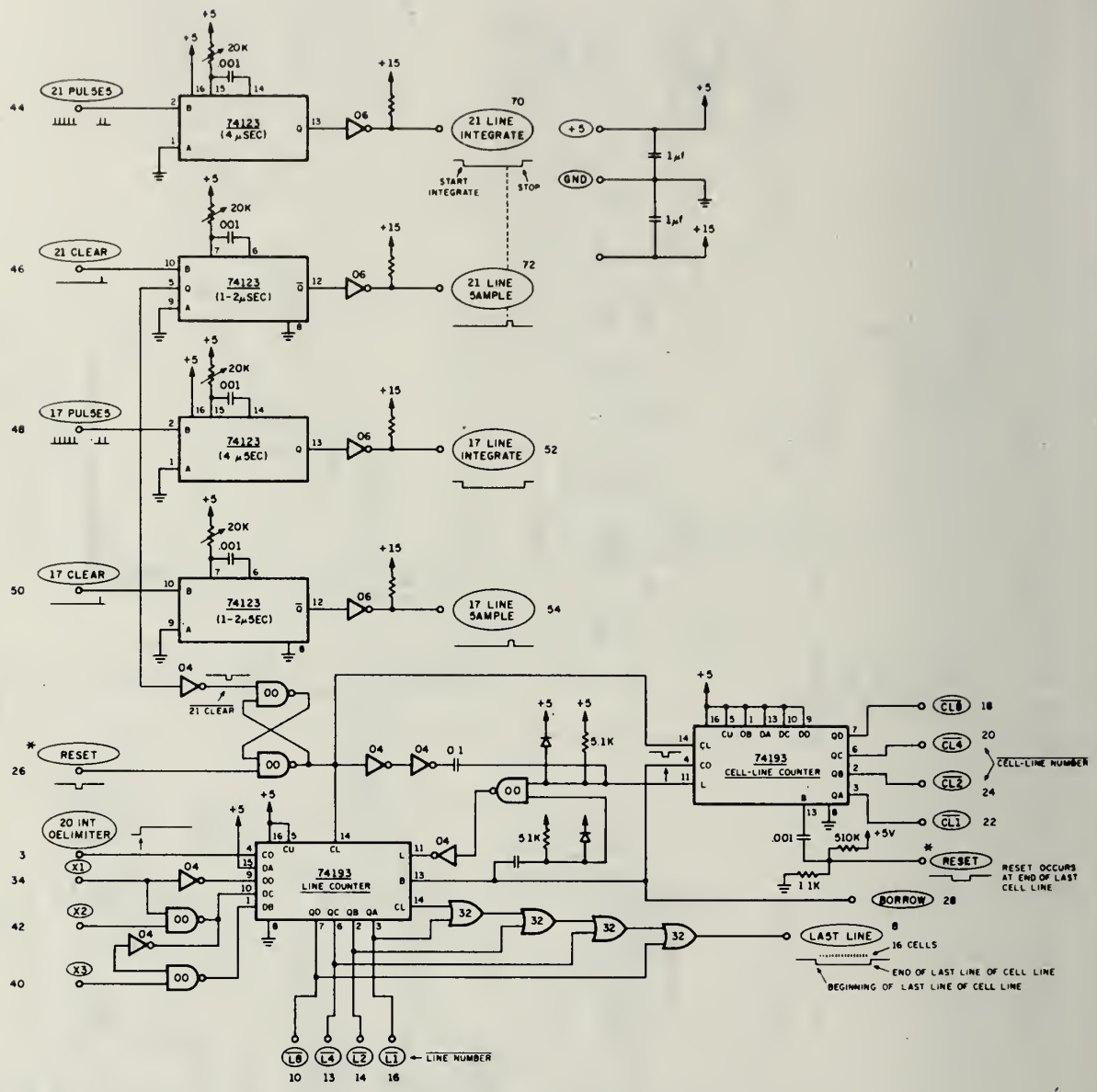
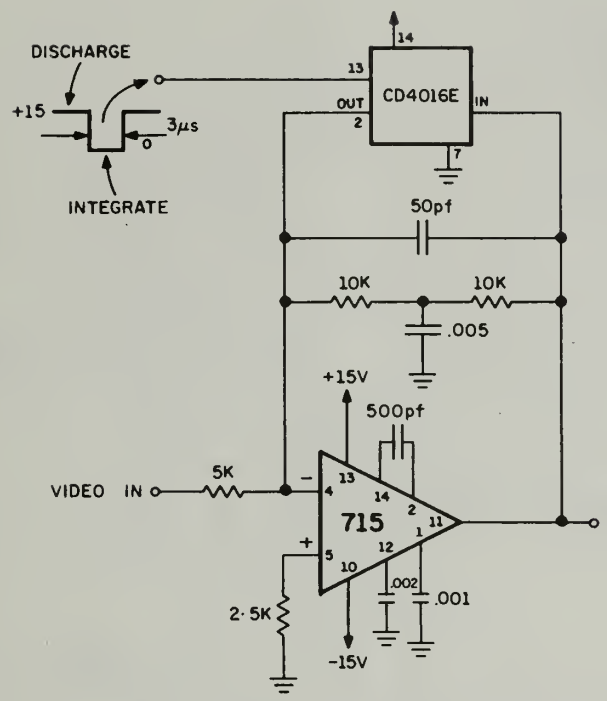
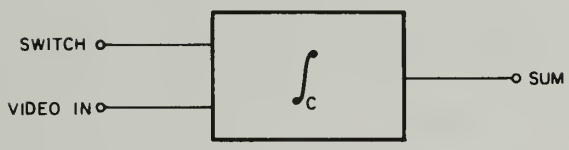


Figure A3. Cell-line Controller

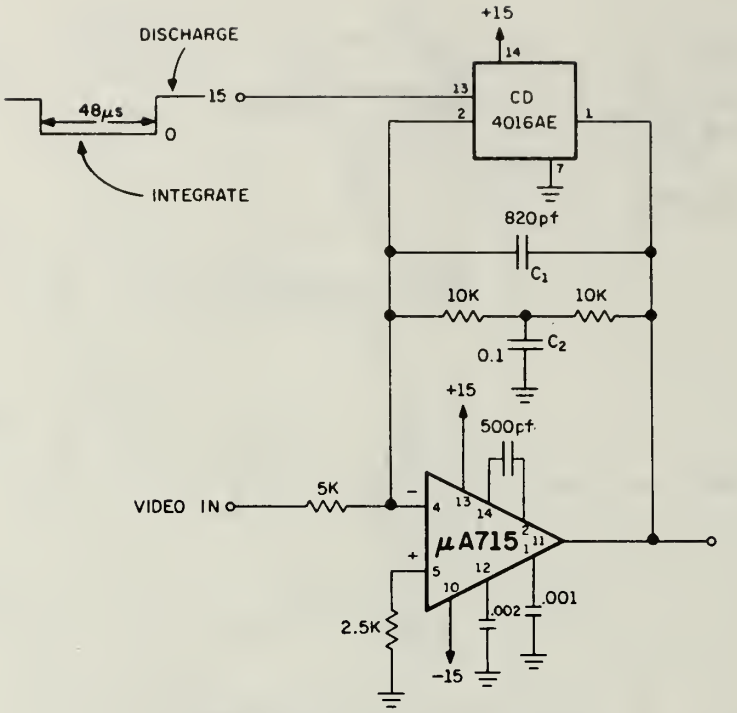


CIRCUIT DIAGRAM OF INTEGRATER AND SWITCH

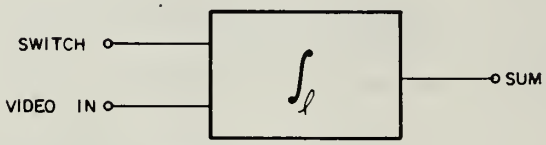


SYMBOLIC DIAGRAM

Figure A4. Cell Integrators



CIRCUIT DIAGRAM OF INTEGRATOR (LINE) AND SWITCH



SYMBOLIC DIAGRAM

Figure A5. Line Integrators

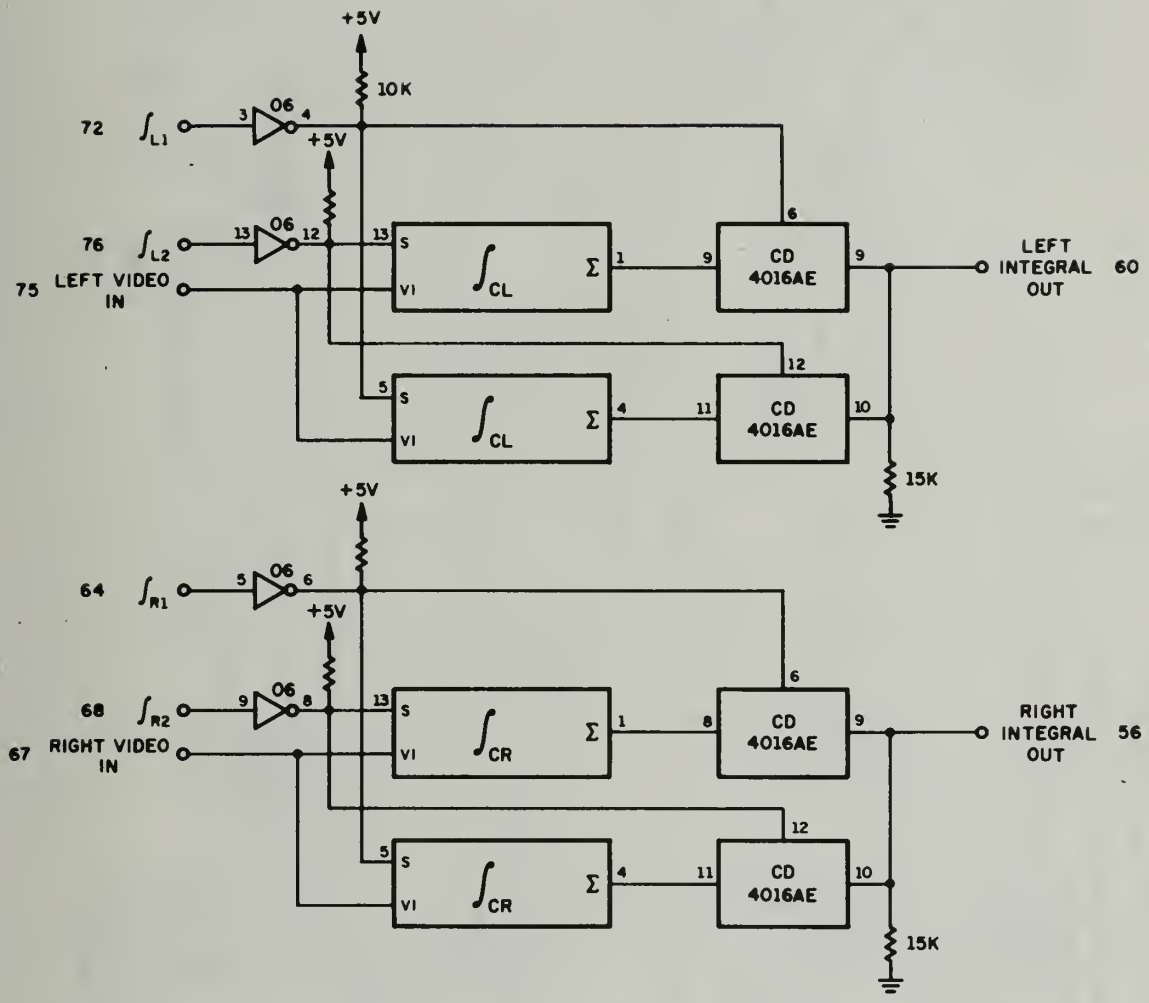


Figure A6. Cell Integrators and Multiplexers

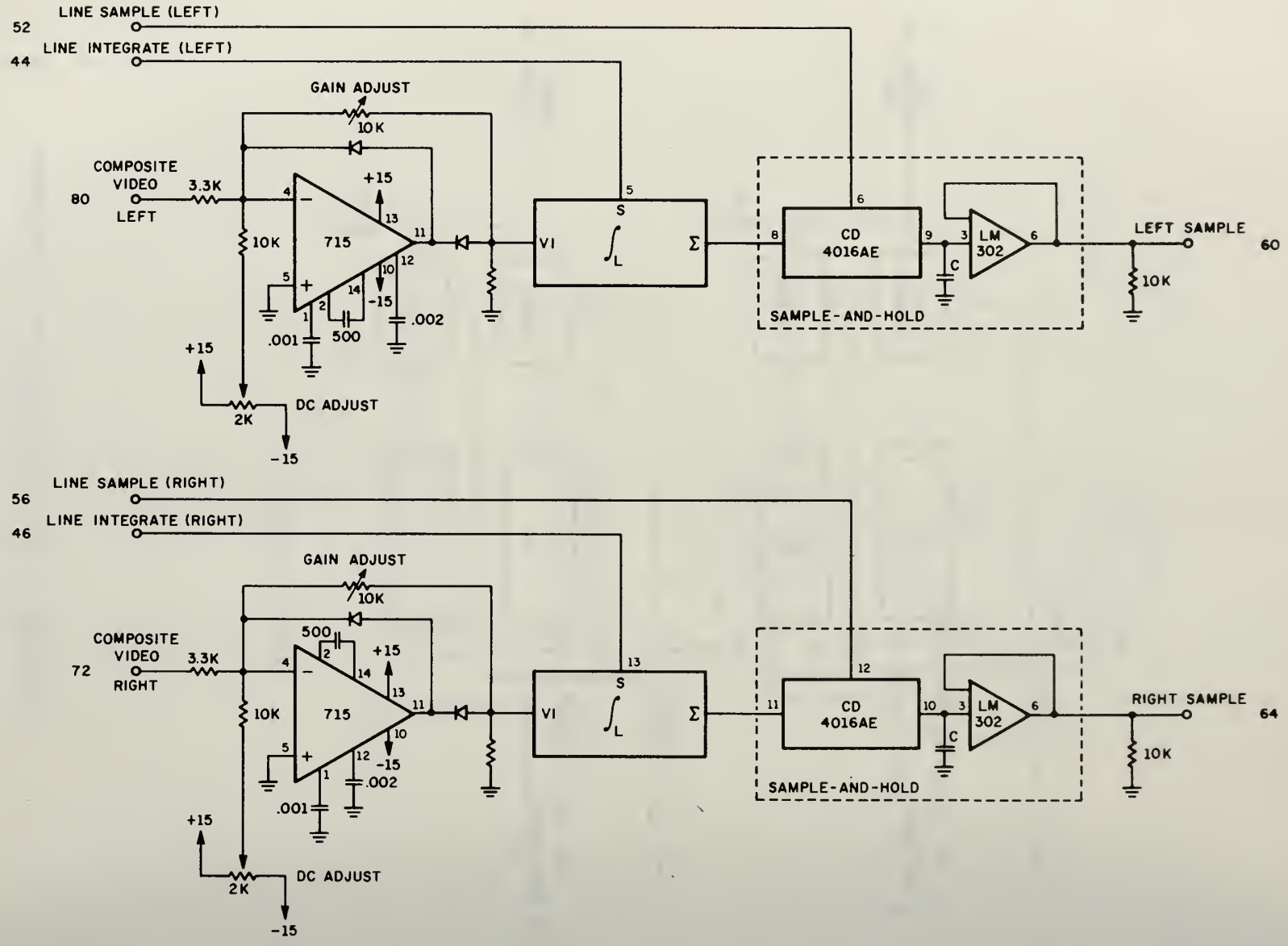


Figure A7. Video Amplifiers, Line Integrators and Sample-and-Hold Circuits

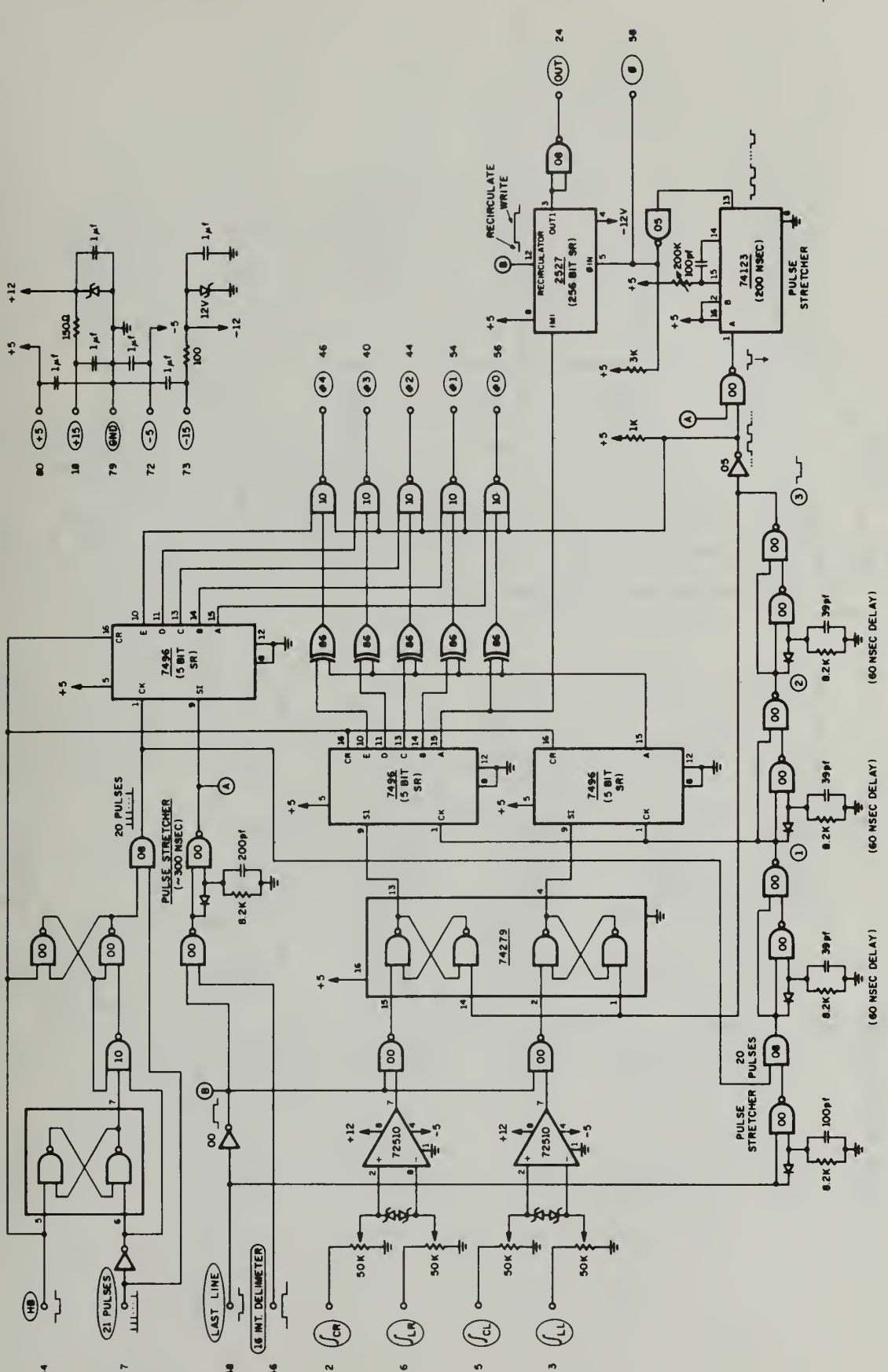


Figure A8. Processor #1

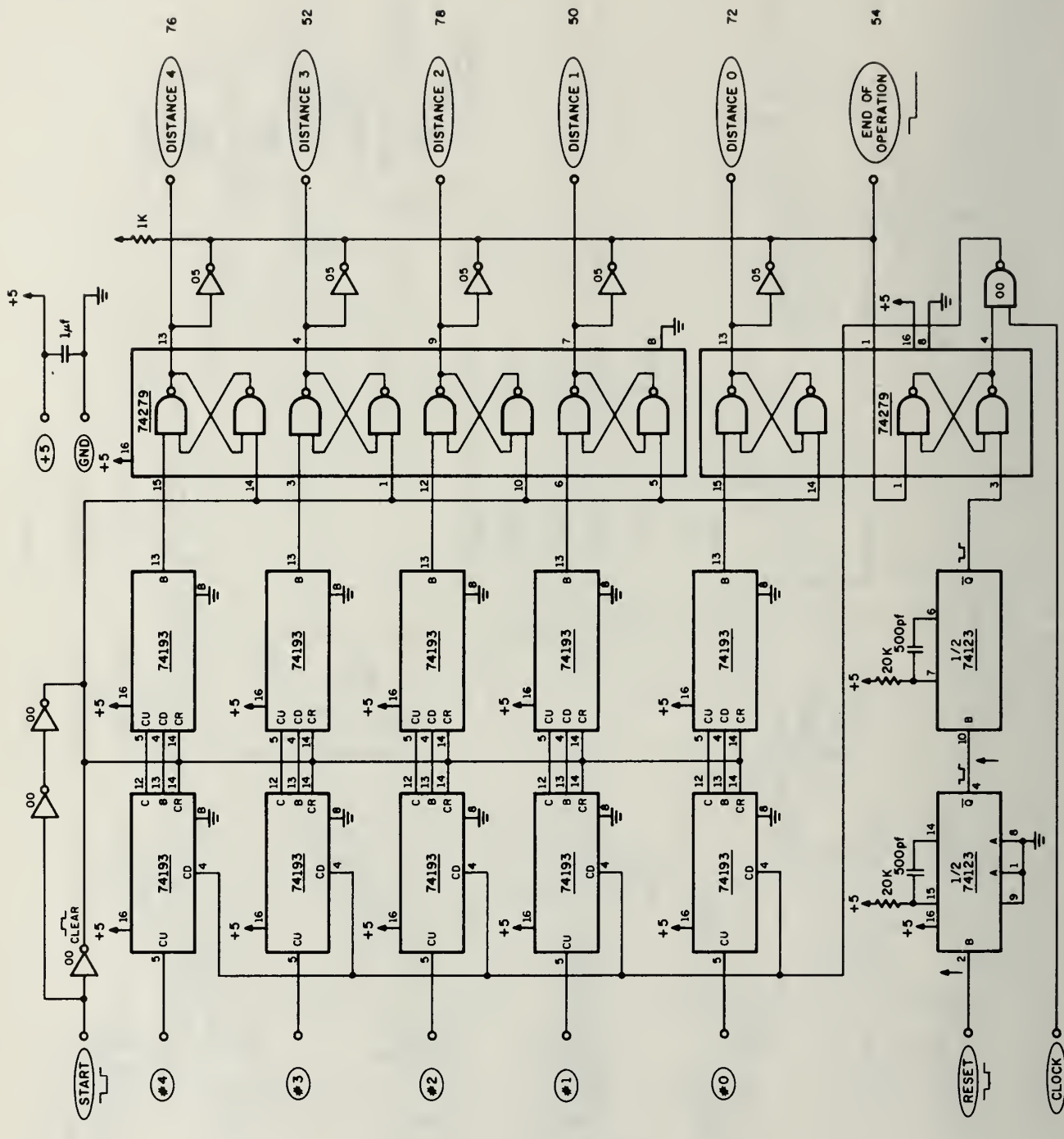


Figure A9. Processor #2

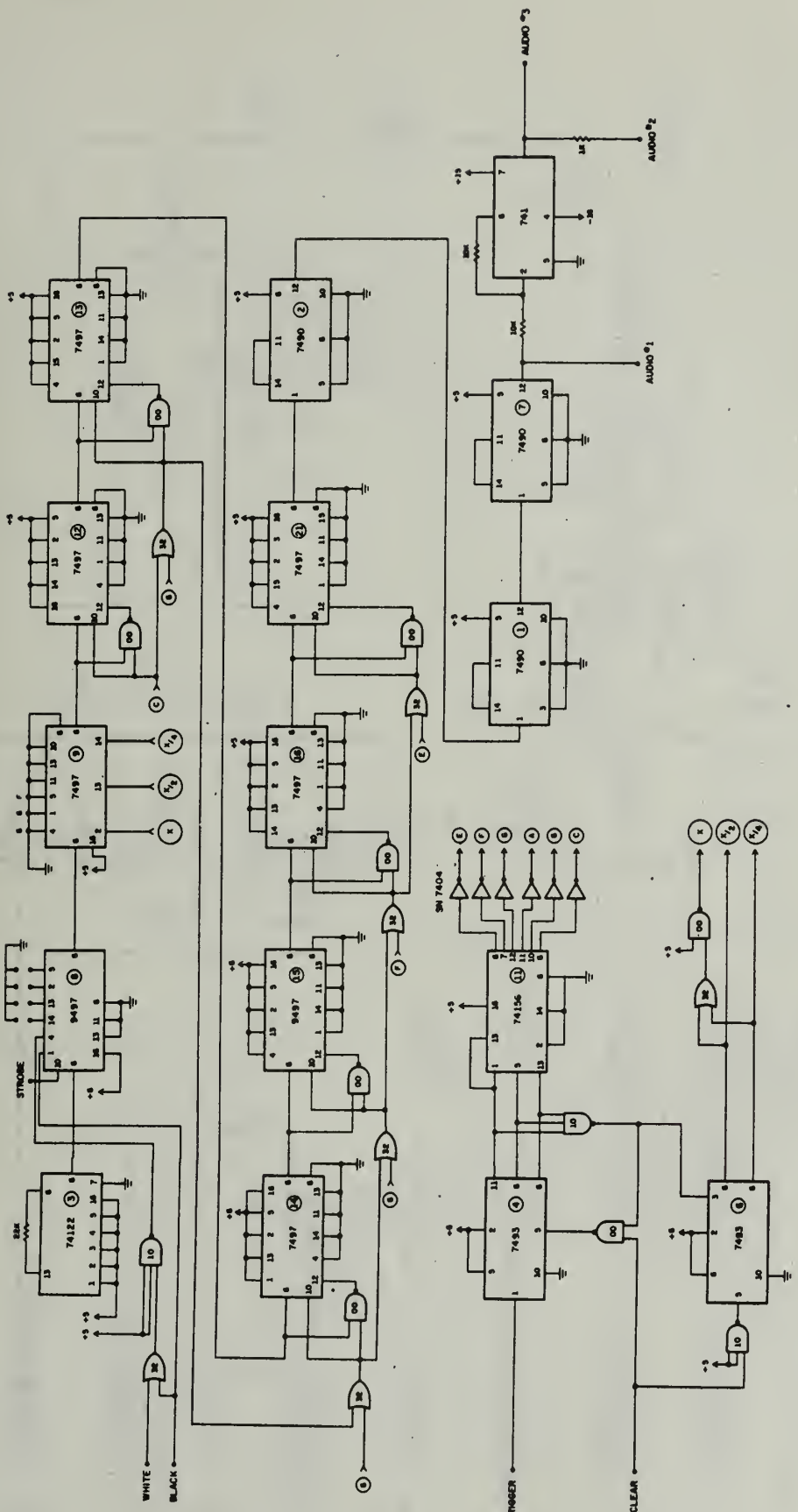


Figure A10. Tone Generator

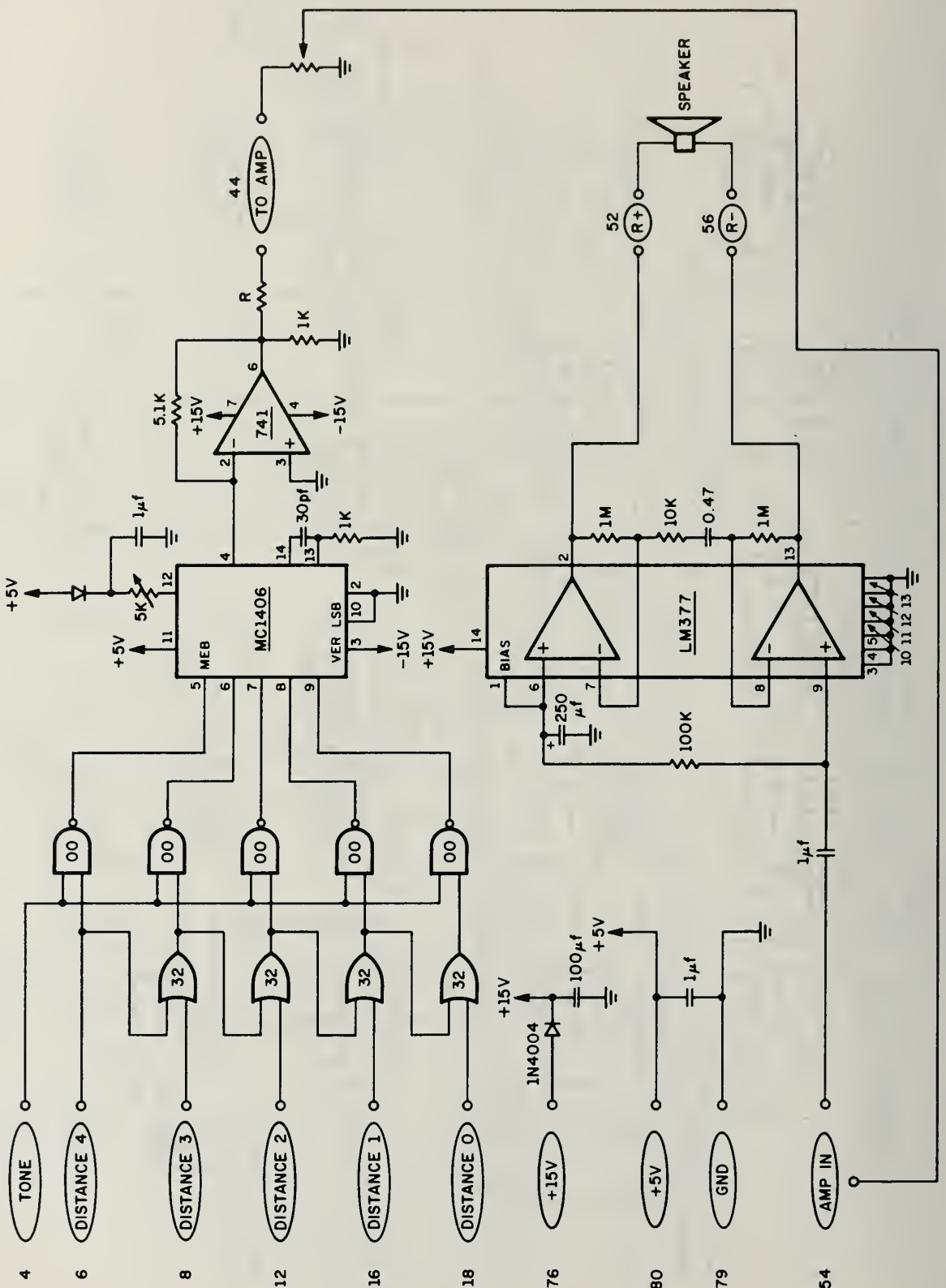


Figure All. Output Amplifier and Level Control

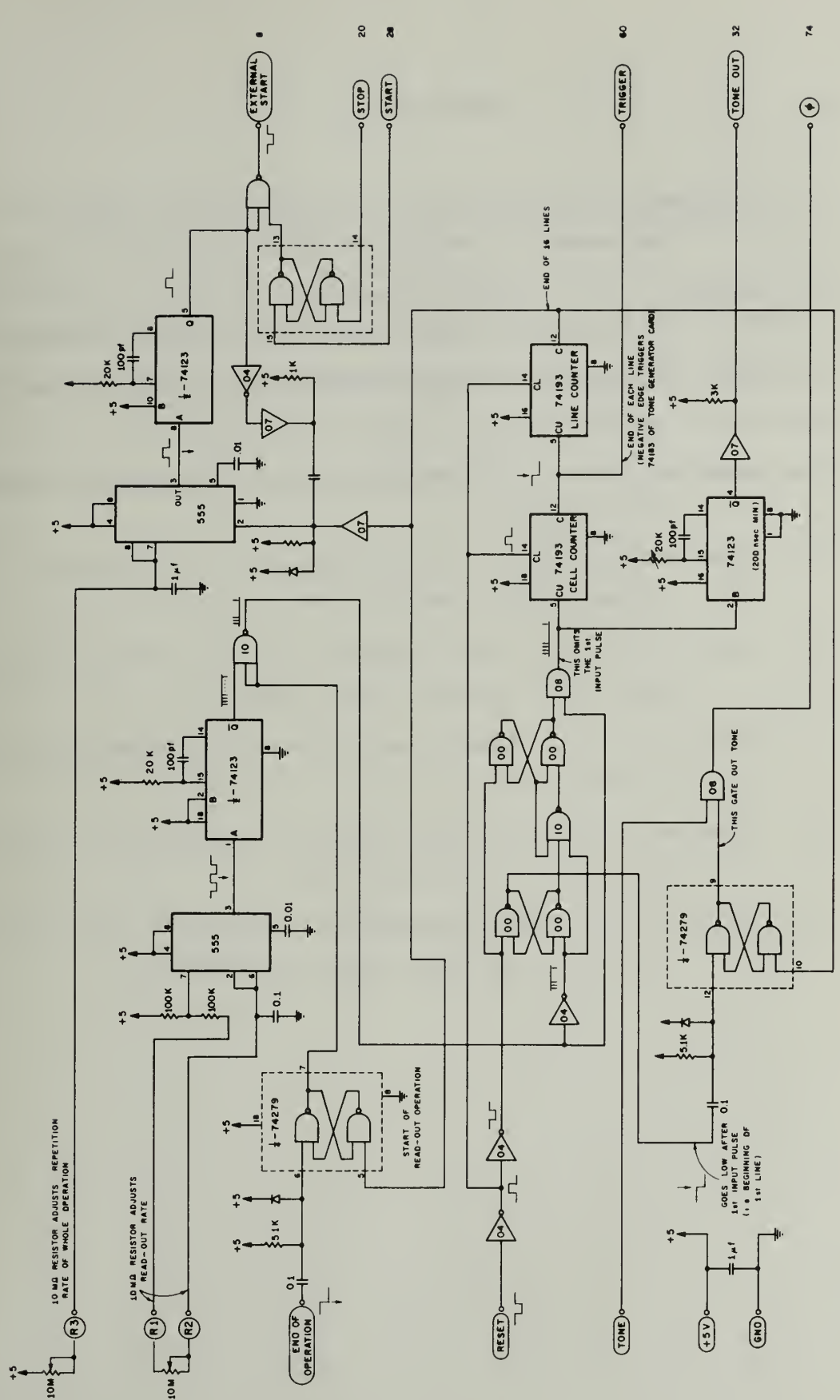


Figure A12. Output Control Circuits

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Vita

Bernard Tse was born on August 2, 1948 in Hong Kong. He received his B.S. in Electrical Engineering with High Honors from the University of Illinois in January 1970 and his M.S. in Electrical Engineering, also from the University of Illinois, in January 1975. He has worked as a research assistant in the Information Engineering Laboratory under the direction of Professor Poppelbaum since January 1970.

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15. Supplementary Notes

16. Abstracts

Caecotron is a project in visual prostheses that derives visual information from two television cameras and outputs the information to the user, namely a visually deprived person, in the form of a modulated tone sequence. The aural picture consists of a 16 x 16 matrix mapped onto the field of the television cameras and the audio system scans across this matrix picture in a way similar to that in which a television camera scans its field. Each of the 16 lines is represented in the aural picture by a distinct frequency and each of the 16 cells of each line is displayed serially: Frequency shifts correspond to brightness variations, while an amplitude modulation of the tone corresponds to the distance of a given element.

17. Key Words and Document Analysis. 17a. Descriptors

Caecotron
Visual prostheses
Television cameras
Modulated tone sequence

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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